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Review

The use of ionising radiation to image nuclear fuel: A review

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ABSTRACT

Imaging of nuclear fuel using radiation has been carried out for decades for a variety of reasons. Two important reasons are Physical Invertory Verification (PIV) and Quality Assurance (QA). The work covered in this review focuses on the imaging of nuclear fuel using ionising radiation. The fuels investigated are both fresh and spent, composed of assorted materials, and in various physical forms. The radiations used to characterise the nuclear fuel include γ, α, β, muons, neutrons and X-rays. The research covered in this review, spans the past four decades and show how the technology has developed over that time. The advancement of computing technology has greatly helped with the progression of the images that are produced. The field began with 2D images in black and white showing the density profiles of γ rays from within an object, culminating in 2013 when a pebble bed fuel element was reproduced in 3D showing each 0.5 mm UO_2 globule within it. With the ever increasing computing technology available to the industry, this can only mean an increase in the rate of development of imaging technologies like those covered in this review.

1. Introduction

The imaging of items across a diverse range of industrial sectors, using radiation is a widely established technique for Quality Assurance (QA) and verification purposes. Within industry, imaging is used extensively to help carry out tasks such as: flaw detection, failure analysis, assembly analysis and tolerance checks. Imaging can be undertaken using a range of radiations and the form of the results can vary widely from black and white density images to full 3D recreations of whole objects and their internal parts.

Of specific relevance to the nuclear industry, ionising radiation has been utilised for imaging during each stage of the fuel cycle for a number of decades with various purposes [Sawicka et al. (1990); Brenizer (2013)]. For example, currently each Pressurised Water Reactor (PWR) fuel rod manufactured, has a record of the cladding welds to prove that they were fully functional when the fuel rod was assembled [Crossland (2012)]. As well as verification, radiography can be utilised to calculate the enrichments of fuel rods, which can be used for safeguarding purposes.

Imaging of Special Nuclear Material (SNM) can be accomplished by various techniques. The two distinct techniques apparent are *passive* and *active* interrogation. Passive detection is when an object has its intrinsic radioactivity measured. Active interrogation is when an object is subjected to a source of external radiation in order to stimulate a response; this is then measured using a detector. *Passive* and *active* are interchangeable with emission and transmission respectively, throughout this paper. Passive interrogation is mainly used for objects with high activity levels, and active interrogation is generally used for materials which would struggle to be detected passively because they have a lower intrinsic activity.

When carrying out active interrogation there are a number of radiations that can be utilised to bombard the object being assayed. These generally fall into one of the following categories: γ-rays, α particles, X-rays, muons and neutrons. Each stimulates a different response, producing data and images that can be utilised in a number of ways. There is also a wide variety of assay times depending on the source material.

Below is a review of imaging techniques that have been used specifically for nuclear fuel assay since its inception in the 1940's. Following that is a discussion about the current state and a summary of future work that may be beneficial to the industry.

No new data were created during this study.

2. Safeguards

The Nuclear Non-Proliferation Treaty (NNPT) was introduced in 1968, the original aim of which was to stop commercial nuclear material being turned into nuclear weapons, and therefore to

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reduce the amount of nuclear weapons being manufactured worldwide. The original signatories were the USA, the UK, the Soviet Union, France and China. Countries which declined to sign, even though they had demonstrated nuclear prowess were Israel, India, Pakistan, Brazil and Argentina. Since the treaty first began, 189 countries have signed up and North Korea is the only country to have withdrawn their membership [Doyle (2011)].

The nuclear industry within the jurisdiction of the NNPT has to conform to a number of safeguarding responsibilities. These activities minimise the risk of nuclear proliferation in two ways; the first is being able to detect the illicit diversion of SNM from peaceful activities to non-peaceful activities in a timely manner. The second is the possibility that detection may occur, which dissuades potential clandestine operators from trying to carry out proliferation activities. As well as the responsibilities held by the nuclear institutions themselves, the International Atomic Energy Agency (IAEA) are an example of a body who perform Physical Inventory Verification (PIV) tasks to confirm that declared amounts and enrichments of nuclear materials are correct. These data, as well as that provided by the nuclear institutions, are used to provide Continuity of Knowledge (COK). Essentially from mining to spent fuel storage, all SNM should have a documented COK trail associated with it.

Nuclear institutions have to counter any credible diversion strategy for SNM. Diversion strategies generally fall into two categories: the removal of nuclear material that is subject to safeguards and the misuse of safeguarded facilities [Shea and Chitumbo (1993)]. This review will only be concerned with the former. The IAEA uses three definitions for the difference between declared amounts of nuclear fuel and the material present, *gross* defect, *partial* defect and *bias* defect. A gross defect is one in which most or all of the material declared is missing from the object. A partial defect is one in which some fraction of the declared material is missing from the object and a bias defect is one in which only a small fraction of the declared material is missing [IAEA (2002)]. Non-Destructive Assay (NDA) has been a staple method in safeguarding, both passively and actively, using various radiation types and employing different methods by which to deduce information about the assayed material [Hsue et al. (1978); Behrens et al. (1979); Runkle et al. (2012); Levai (1982)]. Safeguarding work pertaining to NDA image production are reviewed below.

2.1. *Partial defect detection*

The largest collection of work into safeguarding technologies works towards the detection of a rod being diverted from an assembly of spent fuel. This scenario is seen to be of particular interest as the spent fuel would contain a potentially significant amount of plutonium which could be used for a variety of clandestine operations. One of the methods by which to detect a partial defect is to carry out a passive assay of the γ radiation being emitted from the spent fuel. This technique is described in Lee et al. (1997); Jacobsson et al. (2000); Jacobsson (2000); Svard et al. (2006); Lundqvist et al. (2007); Jacobsson Svaerd et al. (2008).

Both Lee et al. (1997) and Jacobsson et al. (2000) use an Algebraic Reconstruction Technique (ART) in order to analyse the data gained during γ assay [Gordon (1974)]. The results of their tomography of a spent fuel assembly were presented in graphical form; this allows the reader to see clearly that a rod is missing or replaced. In Lee et al. (1997), the graphs produced are two dimensional and the reader may only observe one row of the fuel bundle at a time, whereas Jacobsson et al. (2000) has managed to assemble all of the cross section graphs from one plane together to make a three dimensional graph which can more easily show the diverted rod.

Svard et al. (2006) and Lundqvist et al. (2007) are able to show a well resolved image of a reconstructed assembly.

Svard et al. (2006), compares three γ tomogram techniques for identifying partial defects in spent fuel. These are namely; Pool-side tomography, a laboratory set-up and in-pool tomography. The pool-side tomography is carried out through the spent fuel cooling pond wall. The fuel bundle used is an 8 × 8 Boiling Water Reactor (BWR) type that had been cooled for 8 years. 3240 detector positions are recorded over the whole assembly. The detectors used in this set-up do not produce an image of the fuel element but a graph is produced which shows the amount of activity at each position within the fuel assembly. It can be seen that with the correct γ spectrum, a missing fuel rod can clearly be identified. In the laboratory experiments mock ups of a fuel assembly are used. These are recreated by filling titanium tubes with granulated copper activated with ^{137}Cs. The aim with this test is to be able to identify a swapped rod and a missing rod. 2072 detector positions are recorded with the time in each position equaling 10 s. Similar to the pool-side measurements, the lab tests also resulted in statistical graphs of how similar each rod was to each other. It can be seen from these graphs that the swapped rod is easier to identify than the missing rod. However, statistically both rod changes are detectable. The mock assembly and tomogram produced can be seen in Fig. 1.

The *in-pool* measurements were carried out at Swedish Nuclear Power Plant Forsmark 2. The equipment used is highly specialist and is described in greater detail in Jansson et al. (2006). The fuel assembly used was a BWR of the *SVEA-96S* variety and had only been cooled for 1 year. With the cooling time being so short, it was decided that the most suitable isotope for tomographic measurements was ^{140}Ba. The research utilised 10,200 detector positions, but the article does not say how long this took overall or per detector position. The bundle set up and the tomogram produced are shown in Fig. 2. This test did not include the removal or swapping of any of the pins, presumably due to the difficulties involved with such a task. The image does however show a very clear likeness to the assembly. In comparison to the laboratory measurements provided above, this image has been made clearer by subtracting the background noise and therefore minimising the impact of contaminant γ rays.

Similarly, Lundqvist et al. (2007) simulated an assembly and the associated tomography (Fig. 3) to show very similar results to Svard et al. (2006). Then another tomograph is produced from measured data for comparison. However, this measured data does not contain a partial defect. Instead it is a spent fuel assembly that had recently been removed from service (Fig. 4). It appears on both the simulated tomograph and the tomograph that uses measured data, that

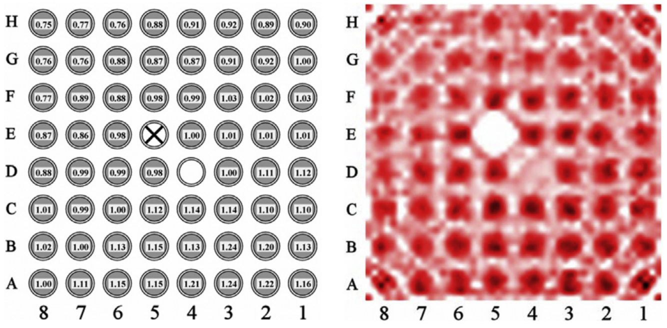

Fig. 1. Laboratory mock up of a BWR spent fuel assembly on the left showing the swapped rod marked by an ‘X’ and the missing rod shown empty. The right image is the corresponding γ tomogram. Image reconstruction using only γ attenuation information was used here [Svard et al. (2006)].