A Tomographic Method for Verification of the Integrity of Spent Nuclear Fuel

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Abstract

Tomographic methods have proven applicable in a variety of fields, e.g. in medicine. This thesis describes a tomographic method developed for measurements on nuclear fuel assemblies and the constraints set by this particular measurement object. The method has been used for verification of the integrity of the assemblies, i.e. for controlling that all fuel rods are present. The application has been examined mainly in computer simulations but also in an experimental study. The method has been proven applicable for the purpose of detecting missing rods; both regarding rods replaced with fresh fuel or fuel-like material as well as rods removed without replacement.

INTRODUCTION

The safeguards system of the International Atomic Energy Agency (IAEA) is a central component of the world society's efforts to prevent proliferation of nuclear material. IAEA has recognised the need to develop methods for verification of the completeness of spent nuclear fuel assemblies, e.g. before placing them in a final repository. For instance, replacement of fuel rods may take place within normal activities at nuclear power plants for technical and economical reasons. Such a procedure introduces a risk that the number of rods is not properly declared. Another conceivable scenario is the removal of fuel rods for illegal collection of fissile material. Such a scenario may imply that rods are replaced with fresh fuel or a fuel-like material.

A possible method to investigate the completeness of a nuclear fuel assembly would be to measure emitted gamma radiation and use the information for tomographic reconstruction of the source distribution. However, the most common algorithms for emission tomography are not valid when performing measurements on nuclear fuel, due to the mix between highly attenuating fuel and much less attenuating water. For such measurements either approximations must be made, involving e.g. an average value of the attenuation, or algorithms must be developed in which the varying attenuation is taken into account.

This thesis is based on the following two papers, which describe a tomographic method developed specially for measurements on nuclear fuel assemblies and the applicability of the method for safeguards. The first paper describes the method, including investigations based on computer simulations. The second paper describes measurements performed in order to verify experimentally the conclusions from the first paper.

I. "A Tomographic Method for Verification of the Integrity of Spent Nuclear Fuel",
S. Jacobsson, C. Andersson, A. Håkansson, A. Bäcklin,
Submitted for publication in Nuclear Technology.

II. "Experimental Investigation of a Tomographic Method for Verification of the Integrity of Spent Nuclear Fuel",
S. Jacobsson, A. Håkansson, P. Jansson, A. Bäcklin,
Submitted for publication in Nuclear Technology.

The method has also been described in the following reports. The author would like to refer to them although they are not included in the thesis.

A. "A tomographic method for experimental verification of the integrity of a spent nuclear fuel assembly",
S. Jacobsson, A. Håkansson, A. Bäcklin, P. Jansson,
Conference proceedings from the 19th annual symposium on safeguards and nuclear management, ESARDA, ISSN 1018-5593. Montpellier, France, May 1997.

B. "A Tomographic Method for Verification of the Integrity of Spent Nuclear Fuel",
S. Jacobsson, A. Håkansson, C. Andersson, P. Jansson and A. Bäcklin,
SKI Report 98:17, ISSN 1104-1374, ISRN SKI-R--98/17--SE, March 1998.

C. "A Tomographic Method for Experimental Verification of the Integrity of Spent Nuclear Fuel",
S. Jacobsson, A. Håkansson, C. Andersson, P. Jansson, A. Bäcklin,
Conference proceedings from the 4th Topical Meeting on Industrial Radiation and Radioisotope Measurement Applications, IRRMA. Raleigh, USA, October 1999. To be published in Applied Radiation and Isotopes.

TOMOGRAPHIC MEASUREMENTS ON NUCLEAR FUEL, SPECIAL ASPECTS.

The tomographic method described in this thesis is called Single Photon Emission Computed Tomography, SPECT, and involves detection of emitted photons from the measured object followed by reconstruction of its internal source distribution. The method has been applied on nuclear fuel assemblies. For the present purpose, the reconstructed source distribution is analysed in order to detect possible missing rods.

The application of SPECT on nuclear fuel implies special conditions:

1) The object is characterised by a highly varying attenuation matrix, as a nuclear fuel assembly typically consists of fuel rods, made of zircaloy tubes containing uranium dioxide, intervened by much less attenuating water.
2) The object is highly radioactive.

The first condition implies that the generally used algorithms, based on Radon and/or Fourier transforms, become invalid. This can be remedied by applying an average value of the attenuation coefficient to the entire object, implying a rather crude approximation as the attenuation is typically about a factor of 10 higher in uranium dioxide than in water. It is also possible to use algebraic algorithms in which the attenuation matrix may be included. Such an algebraic method has been developed and applied in this thesis, as described in paper I.

The second condition has implications mainly on the equipment. It is needed to shield personnel and measurement equipment from the radiation field. The fuel assemblies are therefore typically stored in water during the measurements. Also, the count rate in the gamma-ray detector has to be limited, involving the use of a heavy collimator. The collimator is also required in order to define the field-of-view of the detector in a certain position.

A DESCRIPTION OF THE METHOD INCLUDING SIMULATION STUDIES: PAPER I.

An emission tomography measurement is performed by recording the gamma-ray intensity in a large number of positions relative the measured object and thereby reconstructing the internal source distribution using the measured intensities. A collimator is used in order to define the sections of the object contributing to the intensity in a certain detector position. The principle is illustrated in Figure 1.

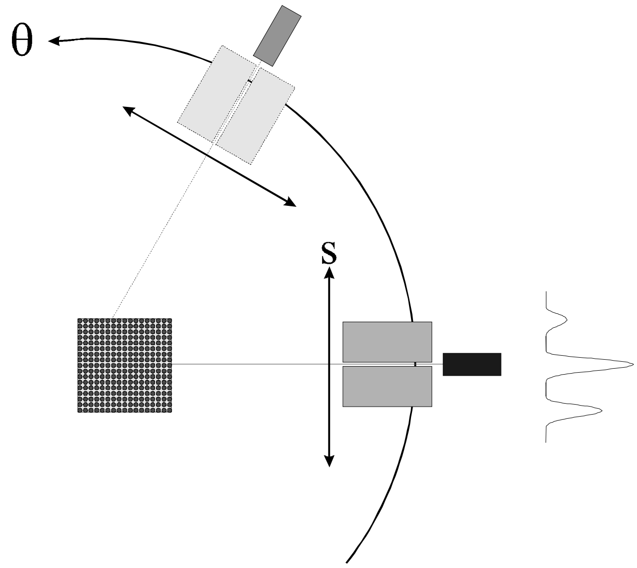

Figure 1. The principle for single photon emission tomography. The collimator-detector system can be positioned in various angular positions θ and lateral positions S relative to the object.

Paper I describes a special-purpose algorithm for emission tomography on nuclear fuel. The measured cross section of the fuel assembly is divided into picture elements, pixels. As an assembly is, in principle, conform along the z-axis such a two-dimensional description is a relevant approximation. The fraction of the emitted gamma quanta from each pixel reaching the detector is calculated theoretically for every position of the collimator-detector system. The intensity in a certain detector position can then be expressed as the source concentration in a pixel times the calculated fraction, summed over all pixels. In this way an equation system is obtained according to:

$$\begin{pmatrix} w_{11} & w_{12} & w_{13} & \dots & w_{1N} \\ w_{21} & w_{22} & w_{23} & \dots & w_{2N} \\ w_{31} & w_{32} & w_{33} & \dots & w_{3N} \\ . & & & & \\ w_{M1} & w_{M2} & w_{M3} & & w_{MN} \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ . \\ A_N \end{pmatrix} = \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ . \\ I_M \end{pmatrix} \qquad eq.\ (1)$$

where w_{mn} = the fraction of the emitted gamma quanta from pixel n theoretically reaching the detector at measuring position m,
A_n = the sought activity in pixel n,
I_m = the intensity in measuring position m.

The equation system can then be solved for the sought activities A in all pixels. The uniqueness of the developed algorithm is the use of beforehand information of the geometry of the measured object. By including this information, the matrix **W** can be accurately calculated, including e.g. gamma-ray transmission through the varying attenuation conditions of the fuel matrix, which cannot be considered using conventional algorithms. However, the algorithm requires detailed knowledge about the geometry of both the measured object and the measurement equipment as well as their positions relative to each other.

The application of the method described above for verification of the integrity of nuclear fuel assemblies involves a complication. If an assembly has been manipulated, the fuel geometry may be perturbed, leading to erroneous calculations of the matrix **W**. It is discussed in paper I that the removal of a fuel rod will lead to a non-zero value of the reconstructed activity in such a position. However, the reconstructed activity is expected to be small enough for the manipulation to be detected.

Paper I accounts for extensive simulations performed of the measurement procedure described above. The application on two main types of nuclear fuel has been investigated, boiling water reactor fuel (BWR) and pressurised water reactor fuel (PWR). Two different gamma-ray energies have been considered, 662 keV and 1274 keV, emitted in the decays of ^{137}Cs and ^{154}Eu, respectively. Two main types of manipulations have been identified:

(a) Replacement of rods with fresh fuel or fuel-like material.
(b) Removal of rods, leaving water-filled positions.

Various configurations of manipulated rods have been simulated in combination with different measurement and reconstruction strategies. The results indicate that the activity in non-manipulated rods can be reconstructed with an accuracy of typically 1-3% (1 s.d.).

For positions of replaced rods (a), reconstructed activities close to zero have been obtained, implying most confident detection of such manipulations. The simulations have indicated that removal (b) also can be detected, although the detection is complicated by the change in attenuation rising from such manipulation. For BWR fuel the reconstructed activities in positions of removed rods have been typically 50-70 %, implying highly significant detection. For PWR fuel the use of the more penetrating radiation from ^{154}Eu may be required in order to obtain confident detection.

EXPERIMENTAL VERIFICATION OF THE METHOD: PAPER II.

To verify the simulations in paper I, an experimental investigation was performed as described in paper II. The measurements were performed at the Swedish interim storage, CLAB, using equipment modified in order to allow for tomographic measurements. The collimator was mounted in the wall of a fuel handling pool, as shown in Fig. 2. The measurements were performed on a BWR fuel assembly with a central rod replaced with a water channel, i.e. like manipulation type (b) above. The internal distribution of ^{137}Cs was calculated using core-analysis codes. The accuracy of these calculations was estimated to be 10 % (1 s.d.).

The detector used was a high-resolution germanium detector, cooled with liquid nitrogen. The gamma-ray field was recorded in various positions relative to the assembly by rotating the fuel and translating the collimator, cf. Fig. 1. Spectra were recorded in 3 240 detector positions, distributed on 40 angular and 81 lateral positions. The positioning accuracy was relatively poor, with estimated angular and lateral uncertainties of up to 1° and 1 mm, respectively.

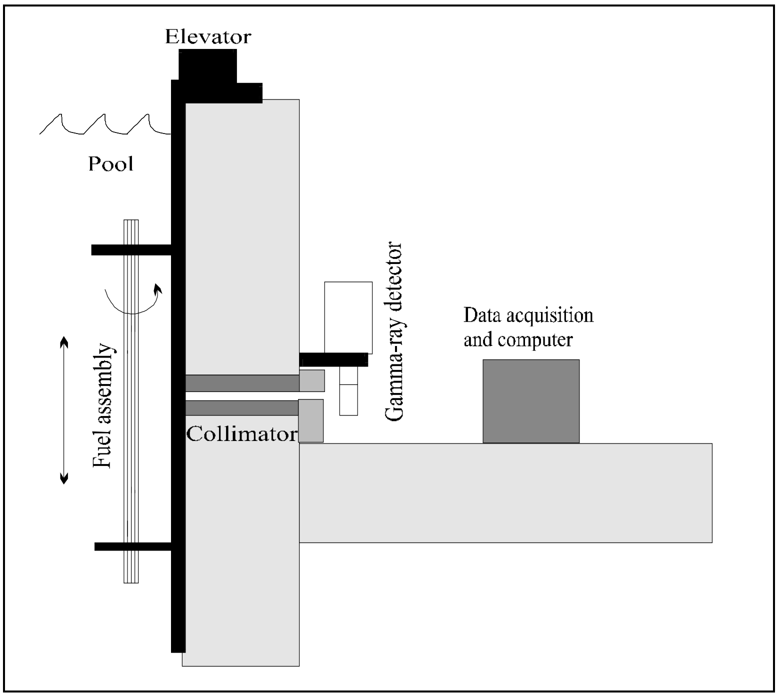

Figure 2. Schematic side view of the equipment used in the experimental study described in paper II.

Analysis were made using the 662 keV and the 1274 keV energies from the decay of ^{137}Cs and ^{154}Eu, respectively. The recorded intensity distributions were in accordance with simulations, justifying the use of simulated intensities in paper I.

Tomographic reconstructions of the internal source distribution were performed using the measured intensities. The deviation between the reconstructed and calculated ^{137}Cs distributions reported in paper II was 7.3 %, i.e. within the stated accuracy of the calculations. The ratio of the reconstructed ^{137}Cs activity in the position of the rod replaced with a water channel to the average reconstructed activity in the other rods was 64.3 %. This is in accordance with the simulations in paper I and allows for confident detection of the replacement.

The use of the more penetrating radiation from ^{154}Eu lead to a reconstructed activity in the position of the replaced rod which was 58.5 % of the average, implying even more confident detection than for the ^{137}Cs radiation. This is also in accordance with the results in paper I.

CONCLUDING REMARKS AND DISCUSSION.

The tomographic method has been proven applicable for verification of the integrity of spent nuclear fuel assemblies. Simulations, described in paper I, have shown that the method is most suitable for finding rods replaced with fresh fuel or fuel-like material, giving highly confident detection of such manipulations. Good results have also been obtained for detection of rods removed without replacement, leading to water-filled positions. The latter case has also been verified in an experimental study, described in paper II.

The equipment described in paper II involves a stationary collimator, situated in a pool wall, implying that the equipment is non-transportable. Such equipment may be feasible where one can expect integrity verification measurements on a more regular basis, e.g. at plants for encapsulation of fuel for final repository. It is desirable to obtain high positioning accuracy in order to detect manipulated rods with high confidence.

There may also be a need for performing measurements on a non-regular basis. Because nuclear fuel assemblies cannot be easily transported, there may be a need to transport measurement equipment to the location of the fuel assemblies. Thus the equipment should be easily transportable, a condition that may be difficult to achieve due to the use of a heavy collimator. It would also be desirable to limit the time needed for the measurements.

The equipment described in paper II involves a large distance between the detector and the fuel assembly. Transportable equipment may be achievable by placing the equipment in the fuel storage pool, implying a more narrow geometry. This would also increase the count rate, which may be used for decreasing the measurement time. The use of more than one detector would further decrease the time needed for the measurements.

One way to enhance the detectability for rods removed without replacement may be to consider consecutive reconstructions using the same set of measured intensities but with various attenuation matrices. By adapting to the change in attenuation rising from the removal of a rod, one may obtain response characteristic for such manipulation.

ACKNOWLEDGEMENTS.

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