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TOMOGRAPHIC TECHNIQUES FOR SAFEGUARDS MEASUREMENTS OF NUCLEAR FUEL ASSEMBLIES

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Abstract

Nuclear power is currently experiencing increased interest over the world. New nuclear reactors are being built and techniques for taking care of the nuclear waste are being developed. This development puts new demands and standards to safeguards, i.e. the international efforts for ensuring the non-proliferation of nuclear weapons. New measuring techniques and devices are continuously being developed for enhancing the ability to detect diversion of fissile material. In this thesis, tomographic techniques for application in safeguards are presented.

Tomographic techniques can non-destructively provide information of the inner parts of an object and may thus be used to control that no material is missing from a nuclear fuel assembly. When using the tomographic technique described in this thesis, the radiation field around a fuel assembly is first recorded. In a second step, the internal source distribution is mathematically reconstructed based on the recorded data.

In this work, a procedure for tomographic safeguards measurements is suggested and the design of a tomographic measuring device is presented. Two reconstruction algorithms have been specially developed and evaluated for the application on nuclear fuel; one algorithm for image reconstruction and one for reconstructing conclusive data on the individual fuel rod

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level. The combined use of the two algorithms is suggested. The applicability for detecting individual removed or replaced rods has been demonstrated, based on experimental data.

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List of Papers

I. T. Lundqvist, *Safeguards aspects of recycling plutonium into MOX fuel in light water reactors*, 28th Annual Symposium on Safeguards and Nuclear Materials Management, ESARDA, Aix en Provence, France, May 22-25, 2007
http://www4.tsl.uu.se/~isv_nuclear_applied/Publications/TobiasLundqvistSalehPaperI.pdf

II. T. Lundqvist, S. Jacobsson Svärd, A. Håkansson, *SPECT imaging as a tool to prevent proliferation of nuclear weapons*, Proceedings of *Imaging 2006*, Stockholm, Sweden, June 27-30, 2006, Nuclear Instruments and Methods A, vol. 580, issue 2, pp. 843-847, 2007, doi:10.1016/j.nima.2007.06.033
http://dx.doi.org/10.1016/j.nima.2007.06.033

III. T. Lundqvist, S. Jacobsson Svärd, A. Håkansson, A. Bäcklin, *Recent progress in the design of a tomographic device for measurements of the power distribution in irradiated nuclear fuel assemblies*, submitted to Nuclear Science and Engineering
http://www4.tsl.uu.se/~isv_nuclear_applied/Publications/TobiasLundqvistSalehPaperIII.pdf

IV. T. Lundqvist Saleh, S. Jacobsson Svärd, A. Håkansson, *Reconstruction algorithms for SPECT on irradiated nuclear fuel assemblies and their applicability*, in manuscript, to be submitted to Nuclear Instruments and Methods A
http://www4.tsl.uu.se/~isv_nuclear_applied/Publications/TobiasLundqvistSalehPaperIV.pdf

1 NUCLEAR POWER AND SAFEGUARDS

The world energy demand is growing constantly; the increase has been more than 50% during the last 25 years and it is projected to grow at about the same rate the coming 25 years [1]. The increase in electricity demand is even stronger and following concerns of supply and the rising prices of fossil fuels together with warnings of a global climate change, there is a renewed interest of energy sources that do not contribute to emissions of greenhouse gases, such as nuclear power. The number of nuclear power reactors worldwide, which is currently about 450 [2], accounting for about 16% of the total electricity production, is believed to increase as several countries are preparing for a nuclear expansion.

However, for this expansion to occur there is a requirement for public and political acceptance of the nuclear power industry. In this context, especially three important factors can be identified; (1) safe reactor operation, (2) nuclear waste management and (3) *safeguards,* i.e. the efforts for ensuring non-proliferation of nuclear weapons. The latter efforts need to be enhanced as the inventories of nuclear materials are increased and new facilities will be implemented. In an effort to address the safeguards issue, this thesis presents work with its primary focus put on safeguards.

Since the first nuclear weapons were dropped over Japan in 1945, states, regional organisations and international regimes have worked for the non-proliferation of nuclear weapons. These safeguards efforts include controls of all technologies and materials and even knowledge that may lead to the development of nuclear weapons and are managed through the International Atomic Energy Agency (IAEA), an organisation belonging to the United Nations.

There is a connection between nuclear power for commercial purposes and nuclear weapons. The relationship is governed by the use of fissile material, specifically certain isotopes of uranium and plutonium. In this context, nuclear power plants, reprocessing plants, enrichment plants and spent fuel storages are typical non-military facilities of interest for safeguards. Inspections at these types of facilities are performed by the IAEA in cooperation with regional authorities such as Euratom in Europe, and national authorities, such as the Swedish Nuclear Power Inspectorate (SKI). However, only states that have signed certain protocols and treaties, e.g. the Non-Proliferation Treaty (NPT), are obliged to allow for inspections. Although most nations have signed these treaties, there are exceptions, e.g. Pakistan, Israel, Democratic People's Republic of Korea (DPRK, renounced 1993) and India (some facilities are under safeguards).

To verify that treaties are adhered to and that data declared by the operators agree with reality, safeguards inspections are necessary. Presently, a number of inspection devices are available, utilising different types of measurement technologies, see e.g. [3]. The tomographic technique described in this work is an example of research aiming towards enhanced safeguards capabilities.

Inspections basically cover two main areas: *accountancy* and *containment and surveillance* (C/S). The former include verification of data declared by the operator and ultimately the goal is to ensure that no fissile material or other relevant materials are missing. In C/S, various types of seals are used to verify that e.g. canisters have not been manipulated with and specific areas are supervised using e.g. cameras.

2 NUCLEAR FUEL AND PLUTONIUM

The reactor core of a typical Boiling Water Reactor (BWR) is loaded with about 500-800 fuel assemblies. An example of such a BWR fuel assembly is illustrated in Fig. 1. The basic constituent of the fuel is uranium. Before being introduced into the reactor the fuel emits practically no radiation, but after irradiation in the reactor the properties of the fuel are changed drastically. The fission products are radioactive and emit radiation as they decay. Other types of nuclides are also formed and of these, the plutonium isotopes require extra safeguards attention, as is further described below.

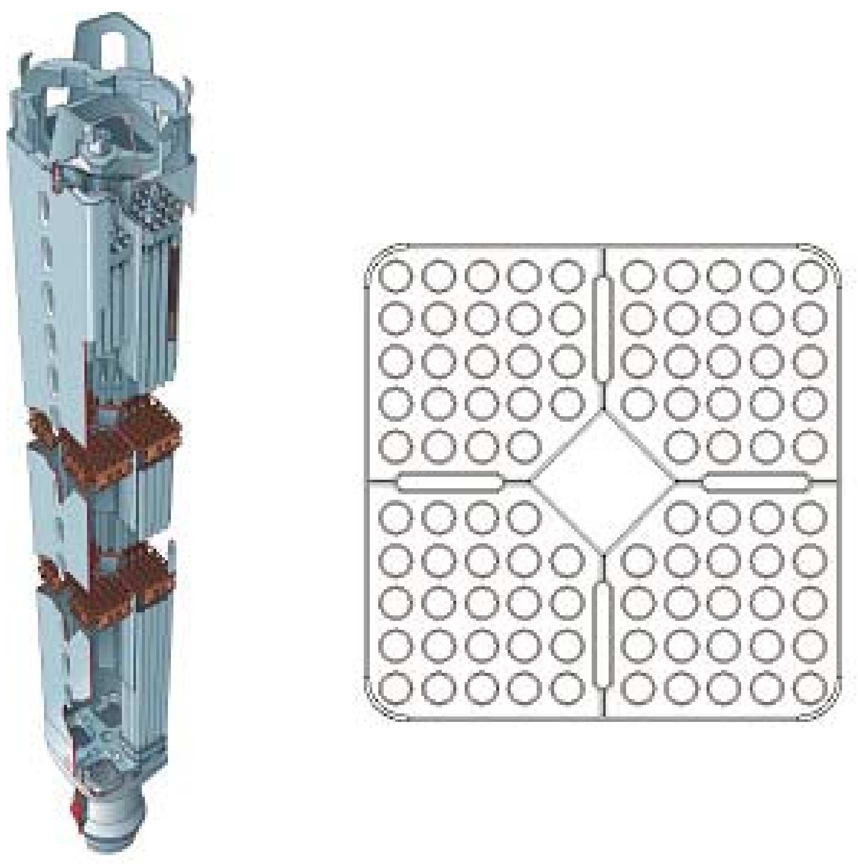

Fig. 1: Illustration of a BWR fuel assembly of the SVEA96-S type (left) and its cross section (right). This fuel type contains 96 fuel rods. The mass is about 200 kg, the length is about 4 m and the cross section is about 15x15 cm^2.

There are basically two alternative fuel cycles, schematically illustrated in Fig. 2. In the *open fuel cycle,* the spent fuel is by definition considered as waste and subject to storage and ultimately final disposal. This principle is utilized in most countries around the world, including Sweden. In the other strategy, the *closed fuel cycle*, the spent fuel is considered to be a resource instead of waste. This cycle additionally involves reprocessing of spent fuel assemblies for subsequent MOX-fuel fabrication and reactor operation. This method provides efficient use of natural energy resources and thus offers benefits from the perspective of sustainable development. Moreover, the separation of plutonium implies a reduction of the nuclear waste, and accordingly decreases the need for repositories.

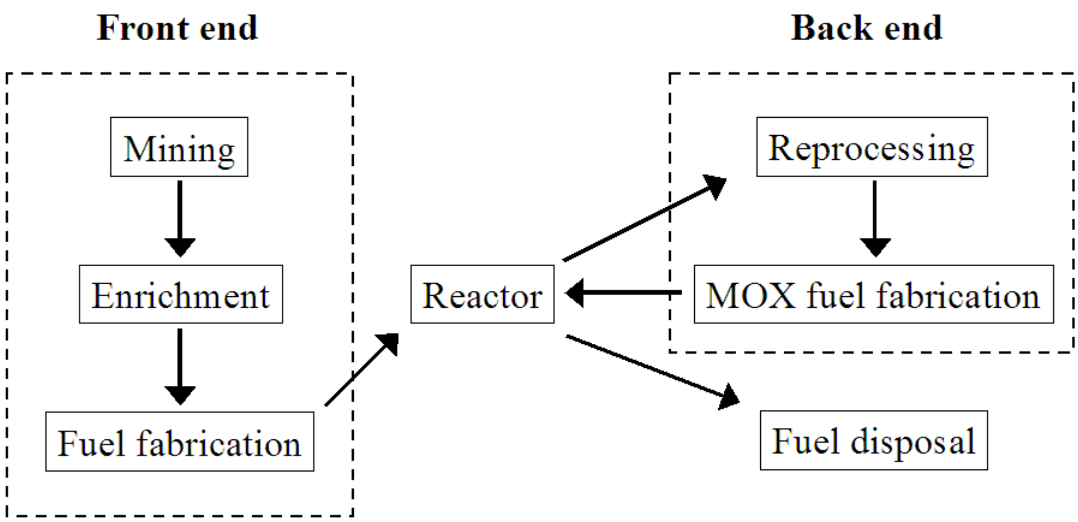

Fig. 2: Schematic illustration of the basic steps in the fuel cycle. The front end of the fuel cycle is represented to the left, i.e. mining, enrichment and fuel fabrication. The back end is represented to the right and involves the activities after reactor operation. The reprocessing, MOX fuel fabrication and further irradiation illustrates the closed fuel cycle.

In future final repositories it will be important to fulfil the safeguards requirements. Here, the fuel will be in a difficult-to-access storage, which is in marked contrast to the reprocessing facilities. The reprocessing is by its opponents regarded as a delicate safeguards issue as it involves plutonium in a separated form. These issues are further discussed below.

In order to understand the safeguards aspects of reprocessing it is important to recognise that there are a number of different isotopes of plutonium, all with different properties. The first plutonium isotope to be produced when nuclear fuel is irradiated in the reactor core is ^{239}Pu and with further irradiation, more isotopes are formed. Accordingly fuel with a short irradiation time has a plutonium composition dominated by ^{239}Pu. Longer irradiation in a reactor will lead to a larger outtake of energy, also referred to as the burnup of the fuel. Fuel with longer irradiation and consequently a higher burnup has a larger content of other isotopes, such as ^{238}Pu, ^{240}Pu, ^{241}Pu and ^{242}Pu.

For production of nuclear weapons the mixture of plutonium isotopes plays a fundamental role. All mixtures could in principle be used to assemble a nuclear explosive device, since all isotopes of plutonium are fissionable by fast neutrons [4, 5]. However, the conclusions in [4, 5] are drawn from a purely mathematical standpoint, without involving the engineering perspective. The most suitable plutonium isotope for a nuclear device is ^{239}Pu and there are several reasons why especially the even-numbered isotopes are not suitable in nuclear weapons, the most important being:

1. Neutron emission from spontaneous fission often leads to pre-initiation of the fission chain reaction, resulting in a sub-optimal and weaker detonation.
2. Heating from alpha decay poses practical difficulties in mounting and storage.
3. Gamma emission poses a radiation hazard to the personnel

Whether or not practically possible to assemble a nuclear weapon from various compositions, the most attractive for a potential diverter of weapons material is indeed plutonium with as large a content as possible of ^{239}Pu. The strongest emitter of neutrons in plutonium of typical spent fuel is ^{240}Pu and based on its relative content, a classification of the quality of a plutonium mixture for explosive purposes has been introduced [6]. In this classification, a plutonium mixture containing less than 17% ^{240}Pu is considered as *high grade*. This is a conservative grading compared to a historical definition of *weapons grade* plutonium, defined as a mixture containing more than 93% ^{239}Pu. A simulation study of the plutonium composition in spent fuel has been performed and some results are shown in Table 1. Values are presented for both UOX- and MOX fuel.

Table 1. Relative content of uranium and plutonium of conventional UOX fuel and MOX fuel. The burnup after two cycles was 20 MWd/kgHM and for the spent fuel it was 50 MWd/kgHM. Both the UOX and MOX fresh fuel have a fissile content of 4%.

	UOX			**MOX**	
	Fresh fuel	**Two cycles**	**Spent fuel**	**Fresh fuel**	**Spent fuel**
Uranium	**100%**	**97.16%**	**93.54%**	**94.14%**	**90.61%**
^{235}U	4%	2.18%	0.68%	0.25%	99.87%
^{238}U	96%	97.45%	98.71%	99.75%	0.10%
Plutonium		**0.68%**	**1.16%**	**5.86%**	**3.97%**
^{238}Pu		0.56%	3.18%	2.50%	3.39%
^{239}Pu		70.41%	49.51%	54.70%	34.09%
^{240}Pu		17.64%	25.02%	26.10%	31.07%
^{241}Pu		9.78%	13.97%	9.50%	16.56%
^{242}Pu		1.61%	8.32%	7.20%	14.88%

Accordingly, only fuel with a low burnup, lower than 20 MWd/kgHM, has a content of ^{240}Pu that would categorize the plutonium as high grade. Typical spent UOX and MOX fuel on the other hand includes too much ^{240}Pu and is by no means optimal for weapons production. Hence, if diversion of plutonium were attempted, low burnup material would be the most attractive target. In this context, **Paper I** emphasizes verification tools for determining e.g. the burnup [7] of nuclear fuel. Moreover, it may be relevant to verify the completeness of fuel assemblies with low burnup, i.e. to ensure that there are no missing fuel rods. For the latter case tomographic techniques can be adapted [8], which is further described in **Paper II**.

3 THE POSSIBLE ROLE OF TOMOGRAPHY IN SAFEGUARDS

As discussed above, irradiated fuel has a content of the fissile isotopes ^{235}U and ^{239}Pu, of which the latter has been produced during reactor operation. Although very difficult, it is theoretically possible to convert this material for use in nuclear weapons. Consequently, irradiated nuclear fuel is subject to safeguards. At safeguards inspections of nuclear facilities, various measurement techniques [3] are employed for verifying the presence and identity of spent nuclear fuel assemblies. As illustrated in Fig. 1, a fuel assembly contains a large number of fuel rods, about 100-300, and techniques are also required for verifying that no individual fuel rods have been removed from the fuel assembly. For this purpose, tomographic techniques have been identified as a strong safeguards candidate by the IAEA [9]. Using these techniques, cross-sectional images of a fuel assembly are obtained and their possible use for safeguards purposes is discussed in **Paper II.**

Fission products being created in the fuel during the irradiation in the reactor are radioactive and generally emit gamma radiation as they decay. The fission products differ in half-life and in the emitted gamma-ray energy. Because high-energy gamma radiation is highly penetrating, it can escape from the fuel material and, accordingly, it can be used in tomographic measurements.

The tomographic measurement technique considered here is called Single Photon Emission Computed Tomography (SPECT) and provides information of the activity of different fission products in individual fuel rods. The measurement technique can be summarised in two basic steps:

1. Measurements of the gamma-ray flux distribution around the fuel assembly. The design of such a device is described in **Paper III**.
2. The reconstruction of the interior source distribution in a cross section of the fuel using the measured data. The applicability of some reconstruction algorithms is investigated in **Paper IV**.

In this work, also a third step has been introduced, namely the post processing of reconstructed images of the internal activity distribution by means of image analysis. The development of such methods is described and further discussed in **Paper IV.** Image analysis is believed to be a valuable tool when verifying that no fuel rods have been exchanged or removed from the fuel assemblies.

The principle of the measuring device used to obtain the tomographic data presented below is schematically illustrated in Fig. 3. Here, four gamma-ray scintillation detectors are used to record the gamma radiation field around the fuel assembly at several positions. A heavy collimator package is used to define volumes in the fuel assembly that can contribute to the count rate at each detector position. A cross sectional tomographic image of a fuel assembly is shown in Fig. 4.

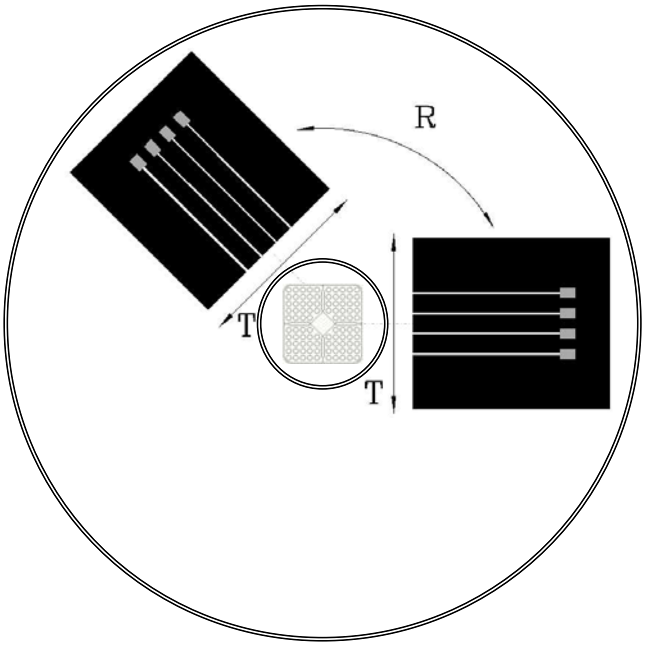

Fig. 3: Schematic illustration of the measurement procedure. The collimator-detector package is translated (T) and rotated (R) into various positions relative to the fuel assembly.

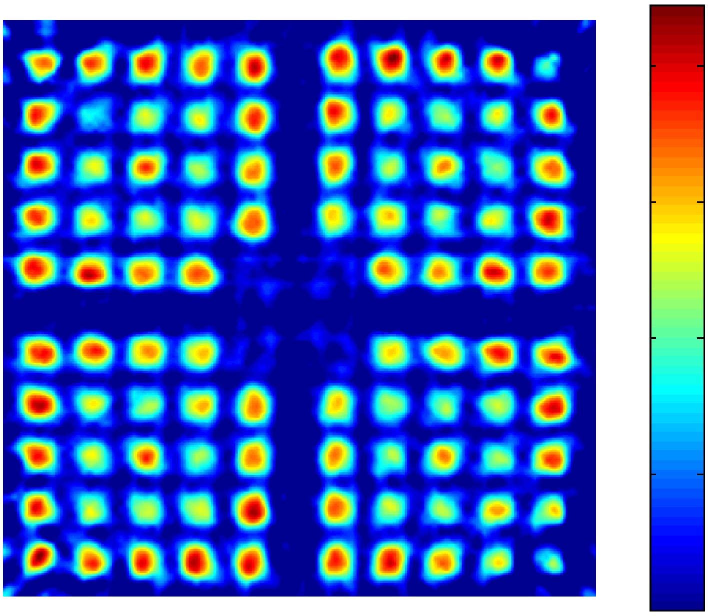

Fig. 4: Tomographic image obtained when analysing data from the measurement of a SVEA96-S fuel assembly at the Forsmark power plant in 2002 [8]. All 96 fuel rods are clearly distinguishable from the background.

Preliminary image analyses on tomographic images have shown the applicability to extract information on the relative position of the fuel assembly in the measuring equipment. The method can also be used for identifying individual fuel rods and determining the background activity level in the image. Accordingly, a procedure for verifying the completeness of a fuel assembly can be foreseen:

1. Tomographic measurements of a fuel assembly and reconstruction of a cross-sectional image.
2. Application of image analysis that determines fuel-rod and background activities as well as the assembly's relative position in the measuring equipment. Possibly, the number of fuel rods may be determined directly.
3. If necessary, available information on the geometry and position of the fuel assembly can be used in a more detailed reconstruction to yield more conclusive data. This procedure is further described in **Paper IV**.

4 THE DESIGN OF A TOMOGRAPHIC MEASURING DEVICE

High demands are put on the tomographic measuring equipment as the fuel assemblies considered here are highly radioactive, each comprising in the order of 1 MCi of activity. Accordingly, the gamma-ray detectors must be shielded by a heavy collimator package. Also, each detector should be equipped with a collimator slit, which defines a specific volume of the fuel that contributes to the detector signal at a certain measurement position, thereby making reconstructions of the activity distribution possible. In the order of 1 000 to 10 000 unique detector positions are required for one reconstruction. Consequently, the measuring equipment has to allow for the recording of the gamma-ray flux in various positions relative to the fuel. The data acquisition system should also have spectroscopic properties in order to be able to distinguish between gamma rays from different radioactive isotopes in the fuel.

A test platform called PLUTO, schematically illustrated in Fig. 5, has been built and used for testing the tomographic technique [10]. A schematic illustration of the data collection in this device was shown in Fig. 3. Successful measurements resulted e.g. in the image presented in Fig. 4 proving the usefulness of the technique. However, the measurements also revealed some weaknesses. The device had a relatively large volume and weight, about 30 metric tonnes, implying difficulties regarding transports and decontamination. Moreover, the construction with a large empty volume about the detector-collimator package led to insufficient shielding of the intense radiation at some measurement positions. Thus, the design of a new measurement geometry, KARON, was initiated, which is described in some detail in **Paper III**.

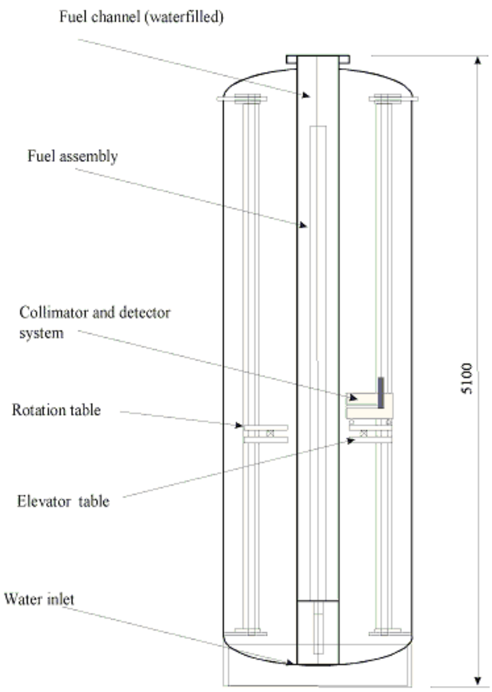

Fig. 5: A schematic view from the side of the test platform PLUTO. The device is used in a fuel handling pool and the fuel is inserted into a central axial water channel.

In common for the two devices is the collimator-detector system that is planned to be re-used in KARON. Here, four gamma-ray detectors of the BGO scintillation type are used mounted in the collimator package that is made of a tungsten alloy. The collimator package is placed on a motor-driven axis, which provides the lateral movement of the collimator package relative to the fuel assembly. The collimator package is illustrated in Fig. 6 including some of its dimensions.

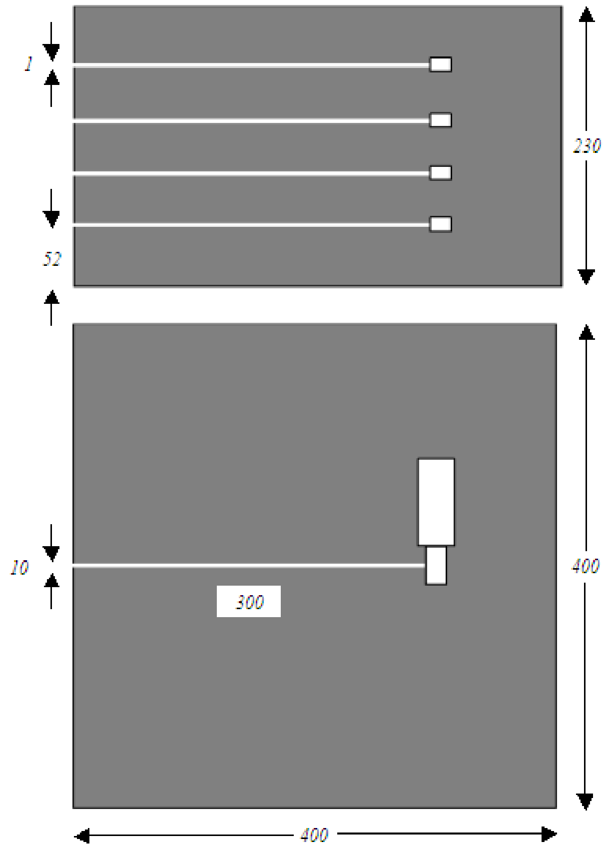

Fig. 6: An illustration of the collimator package, including four gamma-ray detectors, being used in the test platform. The width, height and length are 230 mm, 400 mm and 400 mm respectively. The collimator slits are 300 mm long. The slits are exchangeable so that the slit width and height can be selected. At the test measurements a width of 1 mm and a height of 10 mm were used.

The suggested design, KARON, is based on the experiences from the test platform but in contrast, KARON will be attached to the pool wall instead of being placed at the bottom of a fuel handling pool. A separate system outside the actual measuring device is used for the elevation and rotation of the fuel assembly. Accordingly, the instrumentation can remain at a constant axial level and angle, which reduces the volume of the device.

The proposed design, schematically illustrated in Fig. 7, consists of three main parts:

1. A fuel fixture, with which the fuel assembly can be moved up and down as well as be rotated about its vertical axis. In Sweden, such a system already exists in the fuel handling pool at every BWR nuclear power plant,
2. A nitrogen filled container, containing the actual measuring equipment, i.e. the collimator package and the detectors. There is also a motor-driven axis inside the container that allows for lateral positioning of the instrumentation.
3. A fixture for safe and steady mounting of the container.

As is shown in Fig. 7, there is a considerable amount of water between the measuring device and the parts of the fuel assembly above and under it. This is the major difference as opposed to the test platform, implying a significant decrease in the background radiation level. Also, the device is much smaller, both regarding the weight and size, and consequently KARON is easier to transport and to decontaminate.

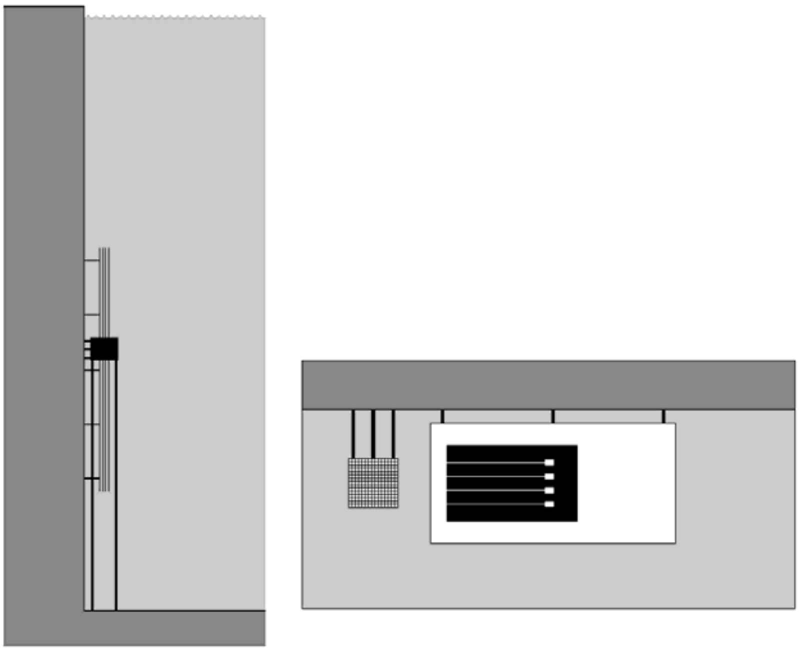

Fig. 7: A schematic layout of the proposed measurement geometry. The fuel assembly is rotated and lifted using an elevator system mounted on the wall of the fuel handling pool as shown in the left part of

the figure. The right part shows a view from above of the collimator-detector package, which is placed in a container that is mounted at a fixed vertical level in the pool.

A detailed analysis of the shielding properties has been performed because that property was considered crucial for the functionality of the device. The investigation was to a large extent based on simulations using the Monte Carlo simulation code, MCNP. The study showed that the total background radiation level in the most exposed measurement positions would be about one third of the direct radiation. This is an improvement of more than two orders of magnitude as compared to the test platform and it was considered to be satisfactory. The total weight of the suggested device is about 3 metric tonnes, which is considered acceptable for the application at the Swedish nuclear power plants. However, a further weight reduction of the device is envisioned that would facilitate measurements at facilities worldwide.

5 TOMOGRAPHIC RECONSTRUCTION ALGORITHMS

As described in section 3, the second step of the tomographic technique is the mathematical procedure to reconstruct the internal activity distribution based on measured gamma-ray intensities. High demands are put on the algorithms, as a fuel assembly is highly inhomogeneous, i.e. attenuation of gamma quanta is strong within the fuel rods and relatively weak in the surrounding water. The large differences in attenuation in different materials imply a large contrast in attenuation profiles for gamma rays having different paths through the fuel assembly.

Two different types of reconstruction methods have been studied, one for reconstructing cross-sectional images of the fuel and the other for obtaining conclusive data on the activity in each fuel rod. For the case of image reconstruction no beforehand knowledge of the internal fuel assembly geometry is assumed. On the contrary, the latter method requires and utilises information of the fuel type and measurement geometry. Both types of methods are considered and **Paper IV** describes two algorithms developed specially for SPECT on nuclear fuel assemblies.

For image reconstructions, fast analytic algorithms have been considered. The algorithm focused on in **Paper IV** has been developed based on a backprojection principle [11] incorporating homogenous attenuation inside the image area [12]. Although the assumption of homogenous attenuation is a strong simplification of the highly varying attenuation properties in a fuel assembly, it reduces some of the artefacts produced by neglecting attenuation. In the algorithm utilized in this work also solid angle effects have been taken into account.

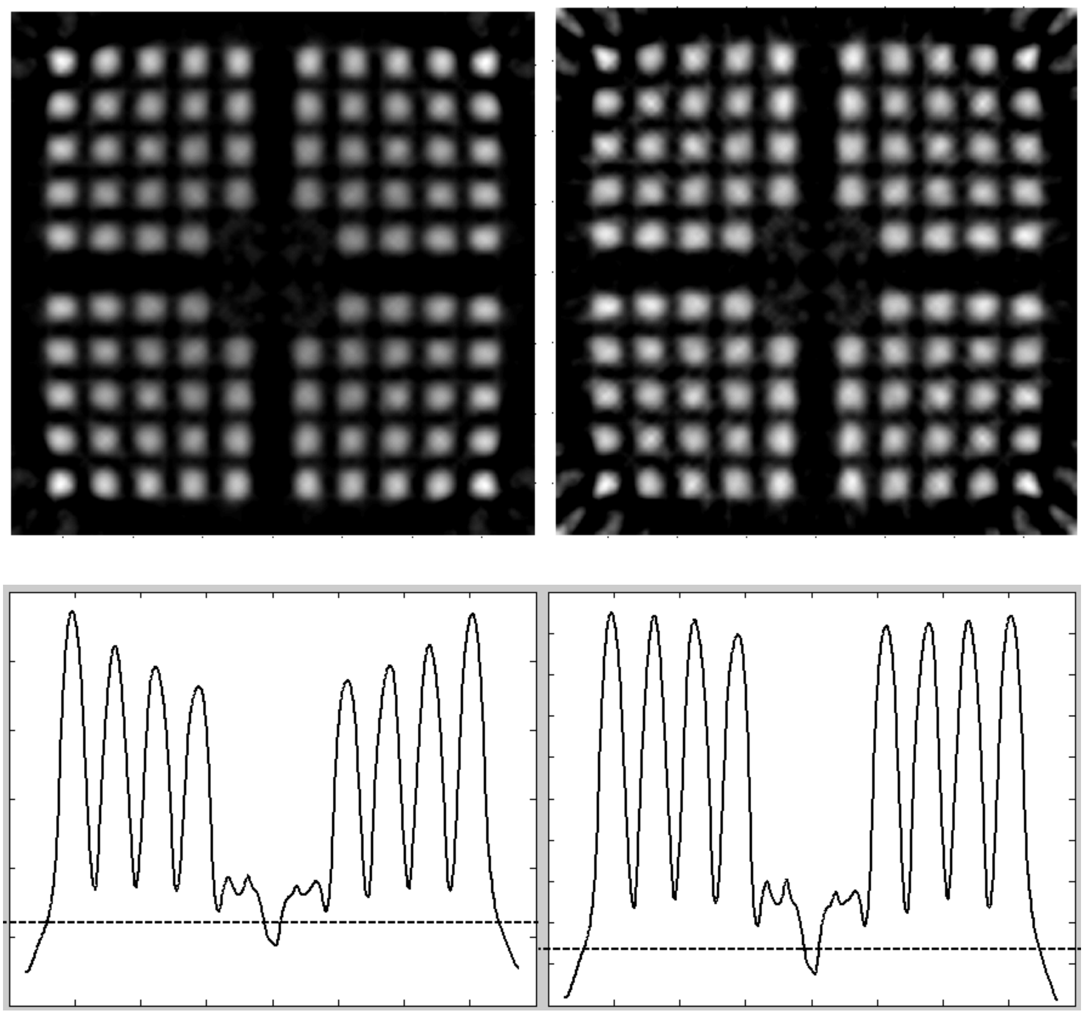

Fig. 8: Reconstructed images using simulated data. No correction was made for attenuation in the algorithm to the left while homogenous attenuation was incorporated into the algorithm developed in this work, yielding images to the right. Below are reconstructed pixel activities from the fifth row of fuel rods.

However, as discussed above, the inhomogeneous structure of a fuel assembly has a large impact on the measured gamma-ray intensities. Accordingly, the precision in the reconstructed activity distribution can be significantly improved by taking into account the fuel geometry and composition to model the gamma-ray transport through the fuel in the tomographic reconstruction procedure. A reconstruction algorithm enabling the use of such information has been developed [8]. The first step in this calculation is the most sensitive part and also the most time consuming. Here, the actual gamma-ray transport in the measurement set-up is calculated [8]. The actual reconstruction is performed in a second step and for this an algorithm called ASIRT [13] has been implemented.

The resulting relative activities in the individual fuel rods from this reconstruction procedure are shown in Fig. 9. Also presented are relative differences between the reconstructed and calculated values using a core simulation code called POLCA-7. The calculated and the measured values agree within 3.0%, i.e. within the stated calculation accuracy of POLCA-7 of 4% [14].

	1	2	3	4	5	6	7	8	9	10
1	0,87	1,10	1,13	1,09	1,10	1,08	1,20	1,10	1,07	0,83
2	1,11	0,70	0,92	0,95	1,11	1,09	0,90	0,87	0,86	1,06
3	1,14	0,90	1,10	0,88	1,04	1,02	0,86	1,04	0,87	1,08
4	1,10	0,94	0,88	0,91	1,11	0,92	1,00	0,86	0,90	1,17
5	1,12	1,11	1,02	1,06			1,05	1,00	1,13	1,03
6	1,12	1,09	1,04	0,95			0,95	0,98	1,05	1,03
7	1,23	0,93	0,87	1,01	1,09	0,98	0,88	0,85	0,89	1,12
8	1,11	0,88	1,04	0,87	1,01	1,01	0,86	1,02	0,84	1,04
9	1,09	0,86	0,87	0,90	1,11	1,03	0,89	0,85	0,97	0,95
10	0,92	1,07	1,07	1,15	1,06	1,05	1,14	1,05	0,96	0,88

	1	2	3	4	5	6	7	8	9	10
1	-9.6	-1.5	0.3	-0.1	-1.2	-1.9	1.6	1.3	0.7	-7.9
2	-0.8	-4.1	2.0	1.7	3.0	2.3	-1.6	1.1	2.0	1.4
3	0.8	0.5	3.1	-0.4	0.6	0.0	-0.9	1.3	1.9	2.7
4	0.3	-0.1	-1.3	0.7	0.8	-6.6	1.8	0.1	2.2	4.2
5	-0.1	2.4	-1.8	-3.9			-2.4	-0.2	4.1	-0.9
6	-0.1	0.7	1.2	-4.4			-3.3	-2.0	2.1	-1.0
7	2.3	0.7	-1.0	2.0	-4.9	-5.1	-1.9	-3.6	-0.7	1.5
8	1.7	1.6	5.1	-3.1	1.3	-1.6	-1.7	1.5	-2.7	0.0
9	-0.7	1.9	2.6	2.6	4.9	3.1	1.2	-1.7	1.0	-4.1
10	-5.6	2.6	5.3	4.2	1.7	1.7	3.2	0.1	-4.2	-11.6

Fig. 9: Measured values of the fuel rod content (left) normalized to an average value of one. Also shown are relative differences [%] between reconstructed and calculated values using a core simulation code POLCA-7.

Moreover, the combination of the two methods described above, *image-* and *rod-activity* reconstruction, is introduced in **paper IV**. The images obtained with a fast analytical method are here used to determine the fuel type and relative position of the fuel assembly utilising image-analysis software [15]. This information can be used in the more accurate rod-activity reconstructions discussed above, providing detailed source-activity concentration in each fuel rod. Accordingly, both the analytic image reconstruction algorithms and the rod-activity reconstructions are important constituents of the tomographic technique and a combination of the two is feasible.

6 CONCLUSIONS AND OUTLOOK

Safeguards aspects play an important role in the commercial use of nuclear power. The implementation of new reactor designs and the anticipated increase of nuclear power imply continuing relevance for research and development of safeguards techniques.

The tomographic technique considered here might be a useful safeguards tool for the future. Two main components of the tomographic measurement technique can be distinguished, i.e., the actual measurement of gamma quanta emitted from the fuel assembly on the one hand and the reconstruction of the cross-sectional source distribution from the measured data on the other hand. The present work has covered both these parts. A new measuring device is envisioned in **Paper III** in which a detailed analysis of the shielding properties has been investigated in Monte Carlo simulations using MCNP. An analysis of different reconstruction algorithms is treated in **Paper IV.** Here it is shown that a combination of two types of reconstructions is feasible, including both fast image reconstructions and more detailed rod-activity reconstructions.

Accordingly, the fundamental parts of the tomographic technique have been investigated. For the future, the methods need to be developed, implemented and tested. Here, a laboratory mock-up [8] is planned to be used, in which the modeling of different types of fuel parameters is possible. Using this mock-up, the ability to detect several types of violations of a fuel assembly’s completeness can be tested, i.e. different scenarios of removal or replacement of fuel rods. Moreover, methods for applying image analysis on the tomographic images will be subject for more thorough studies.

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