COMPUTED TOMOGRAPHIC METHODS FOR NUCLEAR FUEL CHARACTERIZATION AND SAFEGUARD

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Received October 12, 1981

Presented by Dir. Dr. Gy. Csom

Introduction

A research project is going on to explore the technical feasibility of examining large bundles of nuclear fuel using a new radiographic procedure called computed tomography (9). The method offers capability of measuring three dimensional distribution of important nuclear parameters inside the fuel bundle. This way information from the interior of the fuel bundle can be gained.

1. Tomographic imaging nuclear fuel bundles

The tomogram is a picture of a slice. The image is displayed as if it had been possible to cut and view the fuel bundle over an arbitrarily oriented plane (but usually over a plane perpendicular to its long axis). A full three-dimensional picture can be obtained by stacking a sequence of such layers.

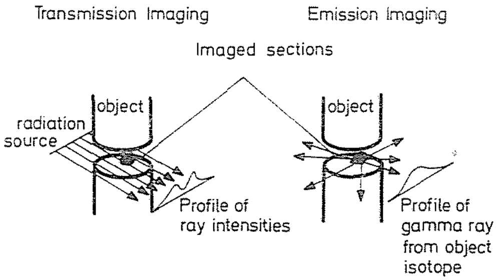


Fig. 1. Tomographic imaging methods

Transmission computed tomography using X-rays or neutrons can be used to determine the internal location of attenuating media. (Fig. 1)

The development of gamma emission computed tomography of irradiated (spent) fuel bundles provides a means of determining the isotopic distributions within a bundle. (Fig. 1)

Computed tomography, either transmission, or emission allows for complete exclusion of section not under study. The section under examination is described by a two dimensional function, which represents the linear absorption coefficient $\mu(x, y)$ in the case of transmission imaging or the radioisotope concentration $\rho(x, y)$ in the case of emission imaging.

2. Principles of the techniques

2.1. *Transmission imaging*

A radiographic imaging aims at determining the spatial distribution of the absorption coefficient μ within an object. In computed tomography this problem is solved by mapping the variation of μ within a sequence of selected planes or thin layers of an object. (Fig. 1)

The basic principle can be quantitatively formulated as follows: a two dimensional section of an object is characterised by a linear absorption coefficient distribution $\mu(x, y)$. Suppose a thin beam of gamma or X-rays traverses the plane along a straight line 1, and the intensities of the incident beam and the beam emerging from the plane are I_0 and I, respectively (Fig. 2) Then

$$I = I_0 \exp\left[-\int_l \mu(x,y)\,\mathrm{d}l\right]$$

or rather

$$\ln\frac{I}{I_0} = -\int_l \mu(x, y)\,\mathrm{d}l = P_\Theta(t)$$

where the line integral (called ray integral or ray sum) is evaluated along the straight line 1.

A set of ray integrals at the corresponding Θ angle forms a projection $P_\Theta(t)$.

The mathematical problem is to find $\mu(x, y)$ knowing the $P_\Theta(t)$ projections at multiple angles. This problem can only be solved approximately because the number of ray integrals, which can be determined experimentially by intensity measurements, is necessarily limited. Better approximation can be obtained if more ray integral are known. Therefore some kind of scanning technique is used where a large number of intensity data are obtained.

The two dimensional function $P(\Theta, t)$ is also called the Radon transform of $\mu(x, y)$. Reconstructing the image is a mathematical inversion of this Radon transform.

2.2. *Emission imaging*

In emission computed tomography the aim is to make cross sectional images of radioactive isotope distribution within an object. Radioactive isotopes are characterised by the emission of gamma ray photons. Fig. 2 shows a selected section of an object with a distributed source of gamma-ray photons in it. A very small, but nevertheless macroscopic element of this source may be considered to be an isotopic source of gamma rays. The number of gamma ray photons emitted per second by such an element is proportional to the concentration of the source at that point. The total number of photons recorded by the detector, having an infinite collimation and neglecting self attenuation inside the object, is a ray integral

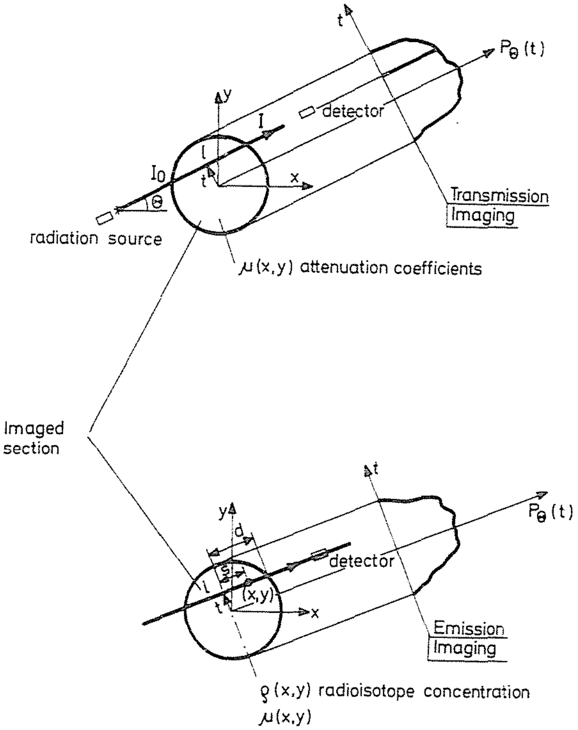


Fig. 2. Principles of tomographic imaging

$$P_{\Theta}(t)=\int_{l}\rho(x,y)\,\mathrm{d}l$$

The problem is to find $\rho(x, y)$ isotope concentration distribution knowing $P_\Theta(t)$ projections for multiple angles, which is the same as in the case of transmission imaging.

In the case of imaging highly absorbent materials like nuclear fuel, the attenuation must be taken into consideration. The projection (Fig. 2.) will be

$$P_\Theta(t) = \int_l \rho(x, y) \exp\left[-\mu(d-s)\right] \mathrm{d}l$$

In emission imaging the so called exponential Radon transform is defined. For the inversion of this transform distribution of attenuation coefficients in the section must be known, otherwise some assumption must be taken. For mapping the attenuation coefficients a transmission image is necessary with the same energy of radiation.

2.3. Scanning techniques

In transaxial computed tomography a single plane is isolated. In the case of transmission imaging, using a source of radiation external to the object, we obtain a transmission picture or projection of the three-dimensional object on a two dimensional surface such as X-ray film or mosaic of electronic detectors. By restricting the measurements to paths contained only in that section, information from other parts of the object is automatically excluded from the data (Fig. 1.). The same is valid for emission imaging, but the external source is missing. The detected radiation passes through or originate (emission imaging) from the desired section without entering other areas.

In Fig. 3 the object (fuel bundle) is scanned by the most common scanning pattern. One source (with a so called pensil beam) and one detector with a collimator are used. These scanners are called translate and rotate systems, in which a source and a detector translate rotate around a scan circle in which the imaged object is located. The scan circle is the region in which the reconstructed attenuation coefficients are valid. Radiation beams are created by tight collimation at the source, transmitted and attenuated in the object of interest and are detected on the opposite side. By traversing the source beam and the detector simultaneously, a set of data (projection) is obtained at a particular angle. The source and detector are then rotated an angle and a new projection is obtained.

In Fig. 3 another scanning pattern is seen, which uses a wide angle fan beam, irradiating the total diameter of the section being scanned, so, that only a continuous rotation of the scanning device is recessary without any additional translation to get all measurement data.

In the case of emission imaging the same scanning patterns can be used, but the radiation originate from the object, and the collimation determines the scanned line.

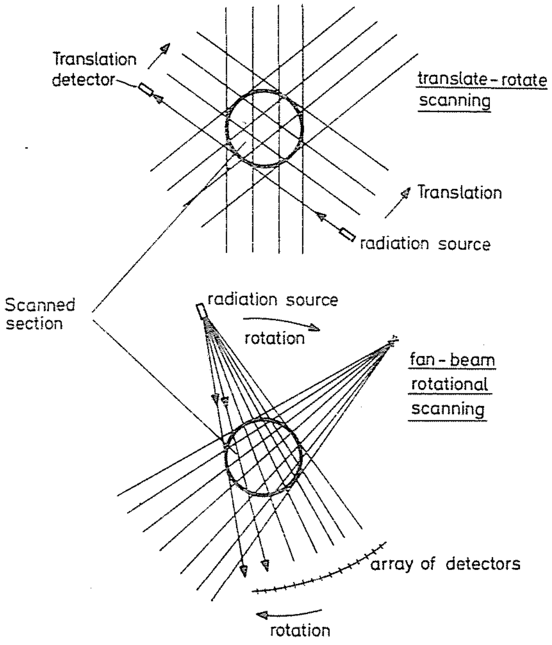


Fig. 3. Scanning modes

2.4. *Image reconstruction from projections*

A reconstruction algorithm tells us how to reconstruct a function from its measured projections. Mathematically, the task is the calculation of a two dimensional function from a set of line integrals.

In the case of transmission imaging attenuation coefficient is utilized for reconstruction, while in the case of emission imaging radioisotope concentration is the quantity of interest.

Many such mathematical algorithms have been developed. There is no consensus as to which method is best. It is likely that different methods are better for different applications.

The data for the reconstruction are said to be complete when the number of projection is sufficient to fully determine the image. In some cases, especially in radioisotope imaging, it may be necessary to reconstruct an image from fewer projections. The reconstruction program must then make assumptions about the missing data. There are analytical reconstruction methods which work well on objects with estimated circular symmetry. In this case it is shown, that two projection are anough for a high resolution image. This fact is extensively used for nuclear fuel section reconstruction [2. 3].

3. Laboratory experiments

3.1. Experimental apparatus

To investigate the feasibility and usefulness of the tomographic procedure for section imaging fuel bundles, experimental apparatuses have been constructed.

A computer assisted tomograph designed for medical applications would be too costly for such a feasibility study. Normally in medicine for high resolution pictures the machine would require an elaborate and expensive detector array and computer. However, if we are prepared to accept lower accuracy, still at the higher resolution required, considerable savings could be made. It is possible to use simpler analogue computing methods. Moreover, it is possible to improve spatial resolution cheaply by the use of an X-ray film instead of a detector array.

Technique theoretically similar to computer assisted tomography are possible using X-ray film as recording medium and incoherent optical methods for realisation of some special mathematical image reconstruction.

Tomography comprises three processes:

a)recording projection: by detecting intensity distribution of radiation transmitted through the object at different directions, which corresponds to the scanning process (Fig. 4).

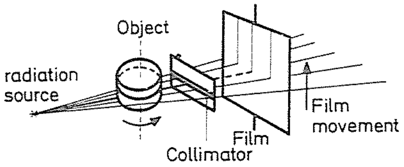


Fig. 4. Projection recorder on an X-ray film (fan beam rotational scanner). The object is positioned on a rotating table, radiation source is fixed

b) reconstruction of the desired tomogram from the recorded projection data. This corresponds to the formation and display of the image matrix in computed tomography.

c) filtering the image matrix, which is realized as a two dimensional analogous convolution. An image processing operation is easy to incorporate in this process. A detailed description of the experimental apparatuses is published elsewhere [7, 8, 9] and we refer to the literature.

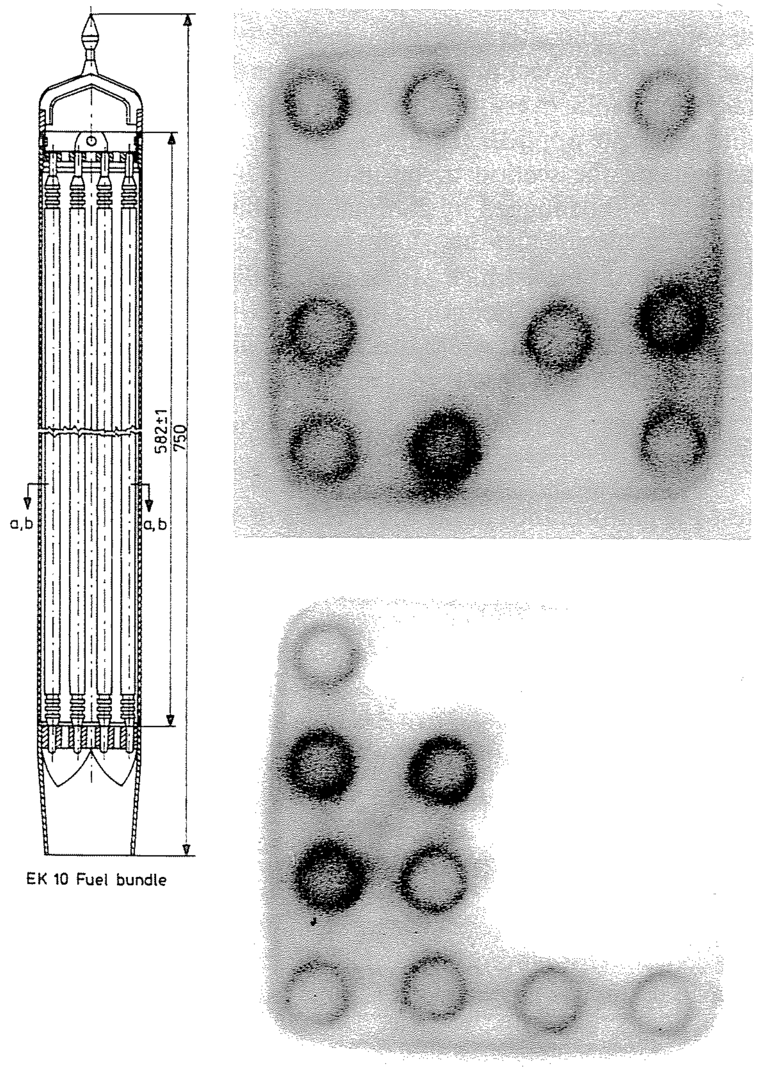


Fig. 5. Section images of demonstration fuel bundles with different rod configurations as reconstructed by the experimental apparatus

3.2. Reduction of background fogging of radioactive objects

The apparatus for recording projections can be seen in Fig. 4 Radiation of the external source having been passed through and attenuated by the object is collimated by a slit before it hits the film. During the exposure the objects rotates about its own axis, which is oriented perpendicular to the beam, and at the same time the film is moved parallel to this axis.

If the object is radioactive, the film is fogged by this radiation. Without the slit (normal radiography technique) each point on the film receives unscreened gamma radiation from every point on the object radiographed. With the moving slit technique applied, the film is screened from all the gamma rays originating outside the section to be imaged. The factor which determines whether the film will be fogged by gamma rays then becomes the activity per unit length of the specimen rather than the total activity. The increase in the activity of the hottest object which can be succesfully imaged is approximatelly in the ratio of the object (fuel) length to the slit width. A factor of more than two order of magnitude with a slit width of 1 mm and our research reactor fuel rod of half a meter length.

3.3. Section images of demonstration fuel bundles

To test the performance of the algorithms of experimental apparatus for tomographic reconstruction of fuel bundles with rod shaped fuel rods, demonstration fuel bundles of the Training Reactor at the Technical University in Budapest have been imaged. Section images of bundles with different fuel rod configurations can be seen in Fig. 5.

The quality of the image depends on the correct filtering operation (choice of filter function) between two extreme cases: low resolution with high contrast and high resolution with low contrast any value matched to the problem can be chosen.

3.4. Conclusions

The first experimental results have demonstrated promising feasibility performing computed tomography for fuel bundle section imaging, and have indicated a number of approaches along which future studies can be recommended.

The experimental apparatuses have some technical imperfections which can be improved. In comparison with the present state of the art of digital computer tomography, this solution seems to offer a higher photographic resolution and a lower sensitivity than that. In cases where cost and simplicity are the primary concerns analog approaches may be the method of choice. Hybrid solutions are very promising to benefit from advantages of both methods.

Digital counting, however, offers the capability of using semiconductor detectors with energy discrimination, which very important when isotope differentiation are of primary goal, as it is for fuel inspection.

Irregulaties on the tomograms can be detected through visual inspection of the displayed imagery or comparison with a reference and displaying only the deviations. This automatic inspection often represents a primary design objective.

For transmission imaging radioactive fuel, a reduction of background fogging can be achieved by the moving slit technique applied, however, highly radioactive spent fuel hardly could be imaged this way. There are two solutions: use of epithermal neutron beam or emission imaging. For on-site work at power stations the emission imaging offers the best solution: modification of the gamma scanning hardware configuration mostly used, tomographic imaging with isotope differentiation could be realised.

4. Emission imaging irradiated nuclear fuel bundles by two dimensional gamma scanning

4.1. Introductory remarks

Feasibility studies have been reported of systems and methods to transmission imaging nuclear fuel. As a further extension of this works, extensive research effort has been made to develop gamma emission computed tomography of irradiated fuel bundles to provide a means of determining the isotopic distribution of important fission and activation products within a bundle. One of our main important tasks in this study is to consider gamma scanning apparatus normally used for burnup measurements at power stations, and to study possibilities for using this hardware configuration for emission imaging.

4.2. Gamma spectrometry of irradiated nuclear fuel materials

4.2.1. Objectives

With the increasing number of nuclear power stations there is a consequent increase in the importance of characterization of irradiated fuel materials. This is necessary for reactor performance evaluation and safeguards procedures. Increased emphasis is placed on nondestructive testing methods.

Among these techniques for irradiated fuels, gamma spectrometry is particularly useful.

Gamma spectrometry objectives can be classified in two main categories: one concerning the determination of neutronic parameters (power history), and the other concenring metallurgical data (fuel condition).

For the power history, the following points can be mentioned:

— qualification of neutronic calculation codes

gamma spectrometry offers the possibility of adding to data for reactor operation monitoring while not requiring complex implementation of destructive examinations. Direct comparison between calculation results and the actual situation of parameters which are closely correlated to power distribution and fuel composition variations is made possible by using nondestructive measurements to determine the precise concentrations of a certain number of fission products, or more generally, the precise distribution at different points in the core or in the bundles.

— Subsequent power distribution examination

Independent of code qualification it can be useful to examine power distribution, either over the whole core or, more finely, inside a fuel bundle or near local heterogenous discontinuities.

— Burnup measurements

Certain long life fission products are characteristic of the burnup rate and once again gamma spectrometry allows the obtention of relative measurements and even under certain conditions, absolute measurements, for burnup. Such determination can be useful under special conditions of irradiation which make the theoretical determination poor or inaccurate.

For the second category (fuel condition), the activity of fission product is not used for determining their concentration and neutronic parameters but for accurately localizing the fuel within the cladding or for examining the physical condition of the fuel.

— Fuel integrity examination

Gamma activity on certain part of fuel likely show fissile stack continuity defects, abnormal stretching, rod deformation, etc. In this case, none of the fission products is of interest, but it is the overall gamma activity which forms the best indicator, from either a precision or localization point of view.

— Detailed examination of defective zones in fuel

In the event of a more or less clearly defined clad failure or the detection of defects in the fuel stacks by integrity examination it is possible to perform finer measurements from both the resolution and the energy aspect, and to obtain, through the clad, information on the structure of defects and the relative quantities of the various fission products.

4.2.2. Choice of fission products

Gamma spectroscopy for determination of parameters of spent fuel has been investigated for a long time. The methods measure the gamma activity of some selected fission product.

Four types of fission products are particularly interesting:

— those of very short life which are practically in radioactive equilibrium at the end of irradiation and which allow the determination of the *power distribution* at this moment

— the isotopes of gaseous or volatile elements which are particularly interesting for determining the *condition of the fuel* .

— gamma ray emitters formed by neutron capture in the fission products; the fission product being produced according to an approximately linear law as a function of the flux, and the daughter product following a parabolic law for which the quotient or power varies from a first approximation with the flux or burnup, and is independent of the total fuel mass.

— those of a long life in relation to the irradiation period, and which give the number of accumulated fissions, representing the *burnup.* A radioactive fission product burnup monitor should have: near equal fission yields for the major fissioning nuclides in the fuel; — low neutron — capture cross sections (including capture by precursors); low migration in the fuel; easily resolvable gamma-ray spectra with high energy gamma rays to minimize attenuation. The radioactive fission products that satisfy most of these criteria are summarized in Table 1.

Table 1

Radioactive fission isotopes for burnup monitoring

Isotope	Half-life	Thermal fission yield (%)		Principal gamma rays	
		^{235}U	^{239}Pu	Energy (keV)	Branching (%)
^{95}Zr	65.5 d	6.50	5.01	724.18	44.4
				756.72	54.6
^{106}Ru—^{106}Rh	369. d	0.39	4.48	511.85	20.6
				621.87	9.8
				1050.39	1.5
				1128.08	0.4
^{134}Cs	2.06	6.75	7.42	569.35	15.4
		(Yield of ^{135}Cs)		604.73	97.6
				795.84	85.4
				801.94	8.7
				1365.00	3.3
^{137}Cs	30.12 y	6.26	6.65	661.64	85.0
^{144}Ce—^{144}Pr	284.4 d	5.39	3.80	696.49	1.51
				1489.15	0.29
				2185.70	0.74
^{154}Eu	8.6 y	0.164	0.285	591.78	4.9
		(Yield of ^{153}Eu)		723.31	19.7
				873.25	11.7
				996.37	10.1
				1274.50	34.7

4.2.3. Measurement principles

Having taken into account the vast field of application for gamma spectrometry as a nondestructive measurement technique, it is advisable to work directly with the best performing semiconductor detectors in order not to restrict the information that can be obtained. For determination of spatial distributions a collimator must be designed and a precise gamma scanning has to be performed.

As a general rule, these are relative measurements between differential spatial points or between the emission at different energies.

The following types of gamma scans have to be mentioned:

— Axial gross gamma scan, which sums all gamma rays having energies above a preset energy level (normally 100 keV) and this sum is plotted as a function of position on the fuel length. It provides a relatively rapid and accurate check for abnormalities in the fuel.

— Axial isotopic scan, which provides information of the axial distribution of the individual gamma emitting isotopes.

— Two dimensional isotopic scan, which is described next and is used for section imaging.

4.3. Two dimensional gamma scanning

Two dimensional gamma scanning techniques have been developed originally to complement one dimensional scanning coupled with chemical analysis. Recent efforts, however, have centered on a nondestructive testing method which does not require sectioning the fuel [2, 3].

The procedure is to accumulate a series of diametral scans, which are tomographic projections, at different angular rotations. These projections are isotopics scans, with a multichannel gamma ray spectrum (written to a magnetic type) at each position. The resulting diametral distributions for a given isotope are used by a mathematical reconstruction program (with a computer) to reconstruct the section image, which will result in a two dimensional distribution of the selected isotopes in the section scanned.

A drawing of how the diametral scan is acquired with a fuel bundle is shown in Fig. 6. As is explained in paragraph 2.2. gamma ray intensities are attenuated as they emerge from the fuel. The attenuation depends on gamma-ray energy and on activity distribution within the fuel. To minimize the attenuation effect, only relatively high-energy fission-product gamma rays are used (see Table 1). On the other hand the oxide fuel density is comparatively high (10.9 g/cm^3). For the 661 keV gamma ray of ^{137}Cs, which is widely used as burnup monitor, the selfattenuation factor within 1 cm diam fuel pin is 0.63 or 37% of the gamma intensity is attenuated within the pin, assuming a uniform activity distribution [6].

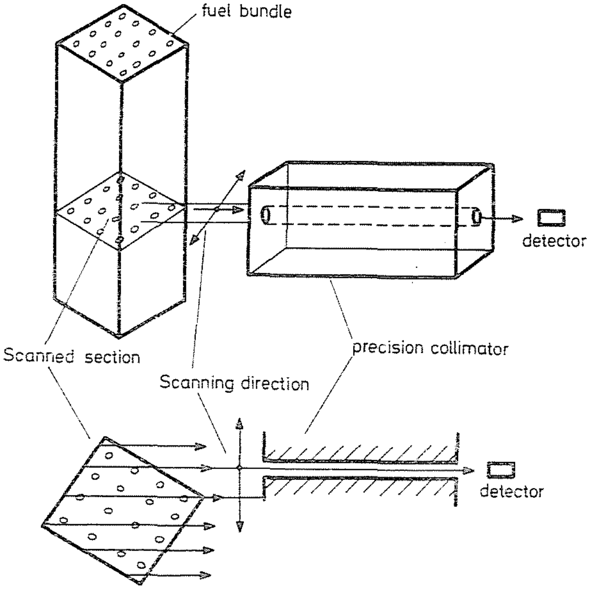


Fig. 6. Diametral scan of a fuel bundle

5. On-site fuel characterization and safeguards by tomography

5.1. Fresh fuel bundles

High energy gamma or X radiation (in the MeV range) can penetrate the large bundle and a transmission tomograph can be made to determine experimentally the internal location of attenuating media. This method needs expensive instrumentation, therefore in its present form it is not recommended at a power station on a routine base. It is valuable for a fuel development program where the high cost is justified.

The only information necessary for an on-site work is reference section images (distribution of attenuation coefficients) at radiation energies used for emission imaging (gamma scanning) spent fuels. Generally speaking: whenever new fuel is being loaded in the reactor there must be a sufficient amount of pre-irradiation data available in order to make on-site fuel examination program meaningful.

5.2. *Irradiated fuel bundles*

5.2.1. On-site gamma scanning procedure

Spent fuel bundles are normally stored vertically as discrete units in a well defined array with identifiable positions.

For water reactors, gamma scanning can be applied to whole fuel bundles or to removable rods which are withdrawn from the assemblies during the period necessary for measurements to be made. Special advantages might be expected using tomography in the case where fuel bundles cannot be dismantled.

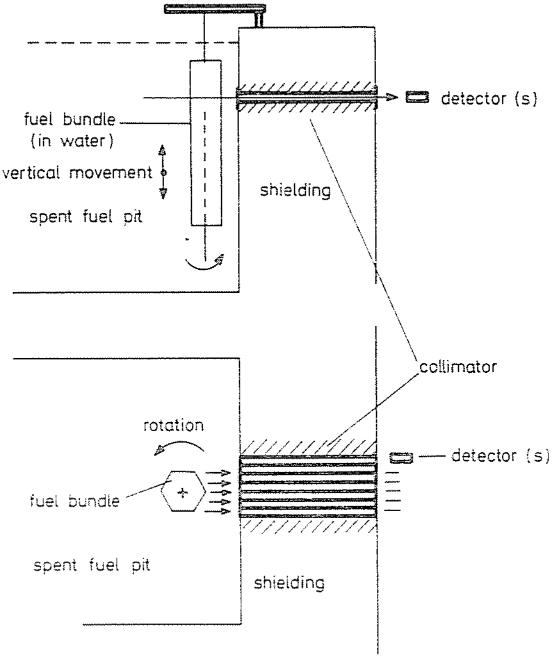
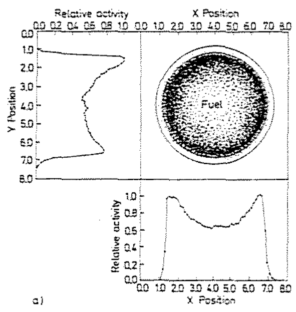
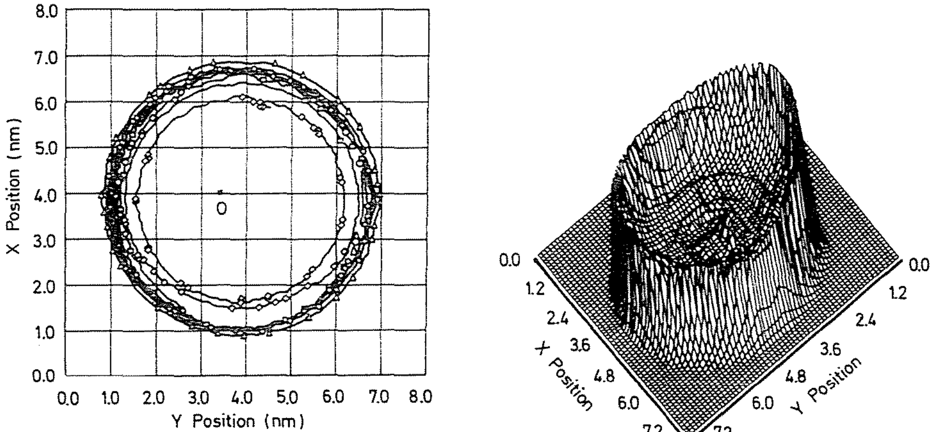


Fig. 7. An arrangement for on-site axial and diametral (two-dimensional) gamma scan of a spent fuel bundle

A gamma scanning apparatus is submerged in the reactor spen fuel pit. An arrangement can be seen in Fig. 7. The fuel bundle is placed on a support having a base which can rotate and move the fuel in vertical direction. A collimator block penetrating the pit wall has a width higher than the diameter of the bundle. A detector arrangement outside the pit contains one or more detectors which are movable in horizontal direction for the scanning process. A recent development of an array of some 200 semiconductor detector might be expected to be fixed to form a fan beam rotational scanner.

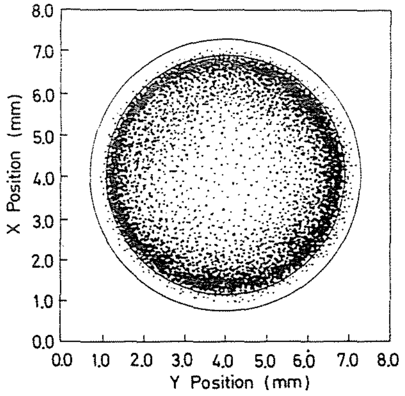




The intensity levels are represented by A (10%), B (30%), C (50%), D (70%), and E (90%).

Contour plot

Isometric projections



b) Density plot

Fig. 8. a. 0 and 90 deg. diametral scanning, b. Contour, two-dimensional density plot and isometric projections for 137-Cs isotopic distribution as reconstructed from two diametral projections (taken from 2, 3)

Fuel bundles to be gamma scanned have to be moved sequentially to the isolated location in the pit.

For an axial scanning the bundle is moved vertically.

At a certain position of the bundle a transverse scanning gives a projection at the corresponding angle, as is described in paragraph 4.3. Rotating the bundle by an angle, but remaining at the same section another projection can be recorded.

The number of measurement points and projection necessary depends on the requirement. If a rough radial distribution of the selected isotopes in a section with an estimated circular symmetry is the task, two projections are required as is published [2, 3].

5.2.2. Evaluation of an emission tomogram

Using the projection data, a tomographic images of the selected isotopes can be calculated by a reconstruction program. A few of the expected most important informations are summarised below:

— Burn up distribution inside the bundle

For some time Cs-137 has been utilized as a burn-up indicator. Variation of this isotope distribution within the bundle are to be considered.

A possible migration of this isotope, as a good demonstration of the benefit obtained by the two dimensional gamma scanning is shown in Fig. 8 which result is taken from (3). A reconstructed image using two projections is shown.

— Safeguard verification by attributes

which mean to verify that the fuel assemblies or bundles in the spent fuel pit have been irradiated and are not dummies that have been substitutted for irradiated fuel. Gross two dimensional gamma scan or selected isotopes can be used for making a section image, giving an exact verification.

Acknowledgement

This work is partially sponsored by the International Atomic Energy Agency. Research contract No. 2467/R1/RB.

Summary

A research project is going on to explore the technical feasibility of examining large bundles of nuclear fuel using computed tomographic methods. The methods offer capability of measuring three-dimensional distribution of important nuclear parameters inside the fuel bundle (burnup data, safeguarding information etc.).

Computed tomography either transmission or emission allows complete exclusion of section not under study. The section under examination is described by a two-dimensional function which represents the linear absorption coefficient in the case of transmission imaging or radioisotope concentration in the case of emission imaging.

To investigate the feasibility of the method for transmission imaging fuel bundles, experimental apparatuses have been constructed and rod shaped demonstration bundles of the Training Reactor of the Bp. Technical University have been imaged and are demonstrated in the paper.

In the case of emission imaging the same scanning pattern can be used as in the case of transmission imaging, but the radiation originates from the object and the collimator determines the scanned line. Objectives of the gamma scanning, choice of fission products are outlined.

A two-dimensional gamma scanning procedure is developed as a possible method for emission imaging irradiated fuel bundle on the station side.

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