Spectral Dose Rate Calculation using Whole Spectrum Processing Approach within Energy Range up to 10 MeV

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ABSTRACT

Gamma ray spectra are usually used for nuclide identification and activity calculation, but could be also used for spectral dose rate calculation. Dose rate spectra calculations in our work are based on whole spectrum processing (WSP) approach, which allows us to calculate initiating gamma ray spectra. A principal step for the WSP application is building up the suitable response operator. Problems are put in an appearance when suitable standard calibration sources are unavailable. It may be occurred in the case of a large volume samples and/or in the analysis of high energy range. Combined experimental and mathematical calibration may be a suitable solution. This paper is focused on building up appropriate response operator for 2” x 2” NaI(Tl) detector with energy range up to 10 MeV by using MCNP code for response calculation.

1 INTRODUCTION

The Peak Net Area (PNA) method is the world-wide accepted technique for analysis of gamma-ray spectra [1]. It is based on the net area calculation of the full energy peak, therefore, it takes into account only a fraction of measured gamma-ray spectrum. On the other hand, the Whole Spectrum Processing (WSP) approach to the gamma analysis makes possible to use entire information being in the spectrum [2] - [5]. This significantly raises efficiency and improves energy resolution of the analysis. A principal step for the WSP application is building up the suitable response operator. Problems are put in an appearance when suitable standard calibration sources are unavailable. It may be occurred in the case of large volume samples and/or in the analysis of high energy range. Combined experimental and mathematical calibration may be a suitable solution.

In the area of NPP, one must discriminate between two different modes of analysis of the gamma-ray fields. One is used in scheduled down time reactor phase and another is in full power reactor phase. Spectra of gamma-ray fields are different during both phases. The energy ranges of up to 2 MeV and up to 10 MeV are typical for gamma-ray sources at the down time phase and at the full power phase, respectively.
2 WHOLE SPECTRUM PROCESSING

The whole spectrum processing (WSP) model is based on the response operator which is mathematically formulated by a vector model

\[ d = K_c q \]  

where \( d \) is a column vector of the measured physical spectrum, \( q \) is a column vector of the real incident spectrum, and \( K_c \) is a matrix of the complete response operator with dimension that corresponds to the length of physical and incident spectra [6].

As an aspect of statistical fluctuation in the gamma-ray spectra, a solution of (1) cannot be found by direct computation of the vector \( q \) (for example by direct inversion of \( K_c \)), and indirect iterative computational methods must be employed [6]. These methods are based on minimizing the residuum between physical and model spectra according to the vector \( q \). The model fitting methods can be classified into two main groups:

a) the least squares (LS) approach, and
b) the maximum likelihood (ML) approach.

Then LS and ML residual functions may be expressed as:

\[ \Delta_{LS} = (d - K_c q)^2, \quad \text{and} \quad \Delta_{ML} = \log(d) - \log(K_c q). \]

Using the residual function of LS or ML (\( \Delta = \Delta_{LS} \) or \( \Delta_{ML} \)), the gradient method yields an iteration step for \( q \) that may be formulated as \( \Delta q = -w \cdot \text{grad}(\Delta) \), where the symbol \( \text{grad} \) represents derivates of the residual function according to all elements in the vector of \( q \) (gradient) and \( w \) is a length of the iteration step [6].

2.1 Response matrix operator \( K_c \)

Only few components of \( K_c \) matrix could be obtained by the measurement. Rest of the responses could be supplemented to the matrix by using Scaling Confirmatory Factor Analysis (SCFA) or by simulation of detector response. SCFA may be used if appropriate calibration sources are available. Only few are obtainable in the energy range from 2 to 10 MeV, therefore a simulation has to be used.

2.2 Response calculations

The goal was to create an universal response matrix \( K_c \) for detector NaI(Tl) 2” x 2”, which model was created in MCNP code. The model with its dimensions is showed in figure 1 and its material composition is described in table 1.
Figure 1: Model of 2” x 2” NaI(Tl) detector

Table 1: Material composition of MCNP detector model

<table>
<thead>
<tr>
<th>component</th>
<th>material</th>
<th>composition</th>
<th>density [g cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>scintillation crystal</td>
<td>NaI</td>
<td>Na:I (1:1)</td>
<td>3.67</td>
</tr>
<tr>
<td>reflector</td>
<td>MgO</td>
<td>Mg:O (1:1)</td>
<td>0.338</td>
</tr>
<tr>
<td>vessel</td>
<td>aluminium</td>
<td>Al</td>
<td>2.7</td>
</tr>
<tr>
<td>surround</td>
<td>air</td>
<td>N:O (4:1)</td>
<td>0.0129</td>
</tr>
</tbody>
</table>

Response of the detector to a mono-energetic source 10 cm from the detector at his axis was calculated. The calculation was done for energies from 10 keV to 10 MeV with step 1 keV. The model was analogue. Tally F8 (detector tally) was used to calculate detector response in active area and it was divided into energetic intervals with width 1 keV. Figure 2 shows the columns of matrix simulated in MCNP code ($K_{MCNP}$) with step 1 MeV. As we can see there, the calculation considers only interaction of the gamma rays with matter of the detector. Peak energy broadening caused by flash collection and amplification in photomultiplier tube wasn’t considered.

Figure 2: Response operator matrix calculated by MCNP code.
Complete response operator matrix $K_c$ could be obtained by multiplication of the $K_{MCNP}$ matrix with matrix of peak broadening $M_{FWHM}$:

$$K_c = M_{FWHM} * K_{MCNP}$$  \hfill (3)

Rows of $M_{FWHM}$ are Gaussian peaks with unit surface under the curve while the position is corresponding to the row ergo energy and the width of peak is corresponding to $FWHM = f(E)$ function. Figure 3 shows FWHM at measured sources and curve fitted to these points.

Values of $M_{FWHM}$ matrix could be formulated as follows:

$$M_{FWHM} = \frac{2^{3/2}\ln(2)}{\sqrt{\pi} FWHM(c)} e^{\frac{-4\ln(2)(R-C)^2}{(FWHM(c))^2}}$$ \hfill (4)

where, $R$ (row) and $C$ (column) are coordinates in matrix and both are corresponding to energy. Complete response operator matrix $K_c$ showed figure 4.
3 DOSE RATE CALCULATION

For calculation of the real incident gamma ray spectra, the WSP method based on operator matrix $K_c$ has been used. The obtained results of WSP represent the spectral photon fluence rates at calibration point distance. The photon fluence rate $\phi \text{[s}^{-1}\text{.cm}^{-2}]$ from a point isotropic source characterized by an intensity $Q \text{[s}^{-1}]$ may be expressed in a distance $R \text{[cm]}$ from the source as

$$\phi(E) = \frac{Q(E)}{4\pi R^2},$$

(5)

where $Q(E)$ characterizes a spectral distribution of source intensity according to photon energy.

In regard to the matrix approximation of spectra used in the mathematical formulation of the spectrum measured, we have analogously introduced a matrix equation for in situ measurement using definition (5) as follows

$$D = KQ = 4\pi R^2 K\Phi = K_F \Phi,$$

(6)

where $K_F \text{[c x c]}$ is the fluence rate response matrix and $\Phi$ is the $c \times r$ matrix with $c$ vectors of the spectral fluence rate as columns corresponding to experimental quantification of the function $\phi(E)$ by $c$ points and $R$ is the distance of calibration point from detector.

Now the results obtained for the spectral photon fluence rates make it possible to evaluate fundamental quantities used in the gamma dosimetry. Exposure rate, $X$, and dose rate, $D$, from mono-energetic photon source can be expressed, as follows

$$X = \phi \begin{bmatrix} \mu_{en} \\ \rho \end{bmatrix} E_0,$$

(7)

$$D = \phi \begin{bmatrix} \mu_{en} \\ \rho \end{bmatrix} E_0,$$

(8)
where $\phi$ is the photon fluence rate, $\mu_{en}$ is the linear energy absorption coefficient for air and water, respectively, $\rho$ is the specific mass of air and water, respectively, and $E_0$ is a photon energy.

A photon fluence rate spectrum put as the columns in $\phi$ which has been acquired as solution of equation (6) and can employed using equations (7) and (8) for determination of the spectral exposure and photon dose rate. For appropriate energies of $E_0$ associated with the values of the fluence rate spectra, energies corresponding to the middles of spectrometric channels have been gradually used.

3.1 Experimental

The method described above was used to analyze the dose rate spectra around nuclear reactor in NPP Mochovce. Gamma-ray fields are different for a down time phase and full power phase, due to different gamma-ray sources. The contaminants of primary circuit are dominating during down time phase, but during full power phase are lap with higher energy sources, which come from neutron interactions, especially capture of thermal neutrons on iron atoms, inelastic scattering on iron atoms and interaction of fast neutrons on oxygen atoms. Gamma-ray energy coming from the contaminants is usually less than 2 MeV, while the gamma-ray coming from the neutron interaction could have energies up to 10 MeV.

The measurements have been performed using the conventional 2” x 2” NaI(T) scintillation detector. Pulses from the detector have been fed into a portable spectrometry system with connection to a PC compatible computer system in following configuration:

- UNISPEC – the universal multi-channel analyzer for scintillation spectrometry, USB connection to host Genie 2000 computer
- GENIE 2000 BASIC SPECTROSCOPY SOFTWARE – for control, displaying and calibration of measurements, parameters setup, PNA calculation
- BOB SPECTRUM DISCOVERY SOFTWARE - for control, displaying and evaluation of measurements using the whole spectrum processing, WSP calculation
- SCINTILLATION DETECTOR 802 – dimension of 2” x 2”, resolution of 7.5 %, including photomultiplier and preamplifier

For the measurement purposes the detection system was calibrated in the range from 10 keV to 9.1 MeV. Set of point sources ($^{137}$Cs, $^{60}$Co and $^{244}$Cm$^{13}$C including escape peaks) was used for energy calibration. Picture 5 shows the measured spectrum (light dots) and the analysis results (dose rate spectra).

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**Figure 5** : Dose rate spectra measured in Mochovce NPP.
4 CONCLUSION

This paper described a new method for gamma ray analysis by using whole spectrum processing approach. Necessary condition for application of this method is existence of response matrix operator in appropriate energy range. Gamma rays emitted around a nuclear reactor under operation can reach high energies, therefore an energy range up to 10 MeV have to be considered. Our work describes a method for creation of such matrix for scintillation detector (NaI(Tl) 2“x2“) using simulation of responses on mono-energetic rays in MCNP code. This matrix was created and used in analyses of spectra measured in Slovak nuclear power plant Mochovce.

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REFERENCES