DELAYED GAMMA DETERMINATION IN RESEARCH REACTORS BY SYNCHRONOUS MEASUREMENTS WITH FISSION AND IONIZATION CHAMBERS

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Abstract

The utilization of intense mixed radiation field inside research nuclear reactor irradiation facilities is mainly determined by the field strength and the level of characterization. Due to short reactor power transients the neutron field can usually be approximated as steady state and adequately characterized by modern Monte Carlo particle transport simulation tools. Characterization of the gamma field requires a more rigorous approach, since it comprises of two contributions: prompt gamma due to fission and prompt radiative capture and delayed gamma due to decay of radioactive isotopes being formed due to neutron radiation, with characteristic decay times spanning from milliseconds to billions of years. This means that even after reactor shutdown, an intense radiation field due to delayed gamma rays exists, depositing energy in reactor coolant, structural materials and irradiation samples, which has to be taken into account in the reactor design.

In the past few years, a joint Jožef Stefan Institute (JSI) and CEA group has been working on an experimental methodology for discriminating prompt and delayed gamma contributions by synchronous measurements with multiple neutron and gamma detectors. The methodology has been applied to the JSI TRIGA Mark II reactor, where reactor was operated in a series of start-ups to steady reactor power, followed by shutdown by rapid control rod insertion steps. Dependence of the delayed gamma fraction on steady reactor power was studied by having the detectors in fixed positions and progressively increasing the step steady reactor power. No distinct dependence of the delayed gamma fraction to total gamma flux on reactor power was observed. We also studied the delayed gamma fraction dependence on detector distance from the core center, by performing a series of reactor power steps up to a 5 kW power level, having a gamma detector at a different distance from the reactor core center. We observed a decrease in the delayed gamma fraction with increasing distance from the core center ranging from 31.4%±2% in the core center, decreasing to 18.9%±2% in the core periphery 10 min after reactor start-up.

1 Introduction

Numerous research reactors are equipped with irradiation facilities, serving as high intensity neutron and gamma ray sources for irradiation of material samples, biological
and electronic component samples, etc. Their usability is determined by radiation intensity strength and by the level of spectral characterization. The latter usually requires a computational analysis, which is supported by experimental measurements of their integral parameters such as reaction rates, detector responses, etc. Due to short reactor transient times and mainly steady state reactor operation, the neutron field can usually be characterized by utilizing steady state Monte Carlo particle transport codes such as MCNP [1], Serpent [2], Tripoli4 [3]. Characterization of the gamma field is a more complex task due to two distinct time dependencies with respect to reactor power: prompt gamma field arising from fission and prompt radiative capture where gamma rays are emitted promptly after neutron interaction with nucleus, and delayed gamma rays which are emitted by neutron activated nuclei with decay times ranging from milliseconds to millions of years, depending on the isotope. In previous work [4, 5] the delayed gamma contribution to the total gamma field has been evaluated by measuring the neutron and gamma signals after reactor shutdown by rapid control rod insertion (SCRAM), utilizing only a few measurement points. Using this methodology the delayed gamma contribution was determined to be roughly 30% of the total gamma field flux.

We have developed a new methodology for determining the delayed gamma field contribution, using multiple neutron and gamma detectors and a synchronous signal acquisition system, which evaluates the delayed gamma contribution time dependence. Due to reactor start-up being performed by withdrawal of control rods from the core and finding the critical rod position, these transients might get misinterpreted as measurement noise. Synchronous readout from all the detectors enables the discrimination of detector noise from reactor transients.

2 Methodology

The methodology we developed relies on having at least one neutron flux detector such as a fission chamber and one gamma flux detector, for instance an ionization chamber. The gamma flux detector therefore measures signals from both contributions, signal due to prompt $S_{\gamma,P}$ and delayed $S_{\gamma,D}$ gamma rays. We assume, that the prompt gamma signal is proportional to the neutron flux and therefore to the signal measured by the neutron detector $S_N$. Using Equation 1 one can extract the time dependence of the delayed gamma field, where $A$ is the scaling factor of prompt gamma signal vs. neutron signal.

$$S_{\gamma} = S_{\gamma,P} + S_{\gamma,D} = A \cdot S_N + S_{\gamma,D}$$

$$S_{\gamma,D} = S_{\gamma} - A \cdot S_N$$  

Equation 1 describes ideal detectors, where the neutron detector in not sensitive to gamma rays, and vice versa. In reality, both neutrons and gamma rays contribute to both detector signals. These contributions can be computationally evaluated as described in [3]. The scaling factor $A$ approximation $A_0$ at a steady reactor power at time $t_1$ (neutron and gamma detector signals stabilize) as described in equation 2. This again is an approximation, since concentrations of long lived isotopes take time proportional to their decay time to saturate, and a reasonable restriction on when the signal is treated as stable must be used.

$$A_0 = \frac{S_{\gamma}(t_1)}{S_N(t_1)}$$  

Since the aim is to determine the relative contribution of the delayed gamma flux, both neutron and gamma detector signals are normalized to their respective values at time $t_1$. This first approximation is used to determine the approximate shape of the relative
delayed gamma signal.

\[ S_{\gamma,D,\text{rel}}(t) = \frac{S_{\gamma}(t)}{S_{\gamma}(t_1)} - A_0 \cdot \frac{S_N(t)}{S_N(t_1)} \]  \hspace{1cm} (3)

The exact factor \( A \) is determined by physics restrictions: the relative delayed gamma contribution is greater or equal to zero and lower or equal to 1 at any time during the measurement. In our case, we use Least Squares method with above mentioned restrictions in order to determine the final parameter \( A \), as described in equation 3.

\[ S_{\gamma,D,\text{rel}}(t) = \frac{S_{\gamma}(t)}{S_{\gamma}(t_1)} - A \cdot \frac{S_N(t)}{S_N(t_1)} \]

\[ S_{\gamma,D,\text{rel}}(t) \geq 0 \]

\[ S_{\gamma,D,\text{rel}}(t) \leq \frac{S_{\gamma}(t)}{S_{\gamma}(t_1)} \] \hspace{1cm} (4)

The uncertainty of the delayed gamma signal is given by equation 2, where \( \sigma_{S_{\gamma,D}} \), \( \sigma_{S\gamma} \) and \( \sigma_{SN} \) are the respective signal uncertainties, \( \sigma_A \) the uncertainty of scaling factor \( A \) as determined by Least Squares method and \( \rho \) the correlation factor between \( S_{\gamma} \) and \( A \cdot S_N \). For evaluation of uncertainties due to measurement noise we propose a time window signal averaging, and taking the distance between maximum and minimum value at each position as a measure of uncertainty. Contribution of neutrons to the gamma detector signal and contribution of gamma rays to the neutron detector signal, as discussed previously are also taken into account as appropriate uncertainty.

\[ \sigma_{S_{\gamma,D}}^2 = \sigma_{S\gamma}^2 + A^2 \sigma_{SN}^2 \left[ \left( \frac{\sigma_A}{A} \right)^2 + \left( \frac{\sigma_{SN}}{S_N} \right)^2 \right] + 2\rho \sigma_{S\gamma} A \cdot S_N \left[ \left( \frac{\sigma_A}{A} \right)^2 + \left( \frac{\sigma_{SN}}{S_N} \right)^2 \right]^{\frac{1}{2}} \] \hspace{1cm} (5)

3 Experimental setup

The measurements were carried out inside the core of the Jožef Stefan Institute (JSI) TRIGA Mark II reactor, which is a pool type reactor with maximum steady state power of 250 kW. The core has 91 available positions in a concentric configuration with diameter of 3.76 cm for U-ZrH fuel elements, irradiation positions and 4 control rod positions for Safety, Pulse, Regulating and Shim control rods (Figure 1), with positions ranging from 900 (fully inserted) to 200 (fully withdrawn). In between these positions, there are also positions with diameter of 10 mm, 8 mm and 6 mm, arranged along two lines across the reactor core, used for miniature detectors (Figure 2).

We used a CEA developed miniature fission chamber (MFC) with a diameter of 3 mm as a neutron detector and a miniature ionization chamber (MIC) of same geometry (Figure 3), but without fissile deposit as a gamma detector. Both were inserted into aluminum guide tubes and inserted into their respective MP positions. An additional PTW Farmer® Ionization Chamber Type 30010 (PTW IC) was used as a reference gamma detector (Figure 4), which was inserted into a thin wall irradiation channel and inserted into F25 position. The axial positions were determined by finding the background radiation maximum.

Two Keithley 6517 electrometers at 250 V bias voltage were used for driving the MFC and MIC, and a Keithley 6587 picocperemeter with bias voltage at 400 V was used for driving the PTW IC. A PC with an in-house developed LabView program was used to synchronously acquire the signal from all three detectors at a rate of 3 s\(^{-1}\).
Prior the actual experiment, the reactor was shutdown for several days in order to decrease the background radiation. The experiments performed were a series of reactor start-ups to a stable reactor power, followed by reactor shutdown by rapid control rod insertion (SCRAM). Two of the control rods (Safety and Pulse) were completely withdrawn, with the other two (Regulating and Shim) inserted as symmetrically as possible. The steps were performed consecutively, starting with the lowest and ending with the highest reactor stable power, limiting each step duration to several tens of minutes in order not to significantly increase the background signal for the next step.

The aim was to try to determine two dependencies: dependence of delayed gamma fraction on reactor power below significant thermal feedback effects, and dependence on distance from the reactor core center. For the delayed gamma fraction dependence on reactor power, MFC was inserted into MP17, MIC into MP25, while PTW IC served as a reference in F25 irradiation channel. Positions of the Regulating and Shim control rods during stable reactor power are given in Table 1. Dependence of delayed gamma contribution on distance from core center was performed at 5 kW power, with MIC being relocated into various MP positions, with different distances from reactor core center, as described in Table 2.
Figure 2: Measurements positions (MP) and the locations of detectors.

Figure 3: CEA 3 mm miniature fission/ionization chamber.

Table 1: Dependence of delayed gamma fraction on reactor power with different reactor power levels along with Regulating (R.) and Shim (S.) control rod positions. MFC located in MP17, MIC in MP25 and PTW IC in F25.

<table>
<thead>
<tr>
<th>Steady reactor power</th>
<th>R. pos.</th>
<th>S. pos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 W</td>
<td>510</td>
<td>511</td>
</tr>
<tr>
<td>500 W</td>
<td>511</td>
<td>510</td>
</tr>
<tr>
<td>5 kW</td>
<td>507</td>
<td>506</td>
</tr>
<tr>
<td>10 kW</td>
<td>508</td>
<td>506</td>
</tr>
<tr>
<td>50 kW</td>
<td>485</td>
<td>485</td>
</tr>
</tbody>
</table>

4 Results

Result evaluations were performed according to before mentioned reactor power up and shutdown steps. For all the positions, neutron contributions to ionization chambers were evaluated at 1% to 3% for MIC and 0.1% to the PTW IC and gamma contribution to the fission chamber signal was evaluated at less then 1%. Correlation factors $\rho$ between $S_\gamma$ and $A \cdot S_N$ were evaluated by calculating signal correlation factors and are $\rho \geq 0.982$. 
Table 2: Dependence of delayed gamma fraction on distance from core center along with Regulating (R.) and Shim (S.) control rod positions. MFC located in MP17 and PTW IC in F25

<table>
<thead>
<tr>
<th>MIC position</th>
<th>Distance from core center</th>
<th>R. pos.</th>
<th>S. pos.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP25</td>
<td>5.2 cm</td>
<td>507</td>
<td>506</td>
</tr>
<tr>
<td>MP21</td>
<td>10.4 cm</td>
<td>508</td>
<td>508</td>
</tr>
<tr>
<td>MP22</td>
<td>13.2 cm</td>
<td>508</td>
<td>508</td>
</tr>
<tr>
<td>MP23</td>
<td>18.3 cm</td>
<td>508</td>
<td>506</td>
</tr>
</tbody>
</table>

4.1 Delayed gamma fraction dependence on reactor power

In Figure 5, delayed gamma fractions are evaluated for different reactor powers and for two combinations of neutron and gamma detectors: MIC and PTW IC with MFC serving as a neutron detector for both. With measurement at 50 W steady reactor power we observe a highly noisy signal which is due to low power. Measurement at 50 kW power for MFC & PTW IC combination also shows a deviation towards the end of irradiation, which was found to be due to the heating of the PTW IC (a vented ionization chamber), thus decreasing the mass of air for ionization [7]. The delayed gamma fractions along with scaling factors $A$ were determined at 10 min after reactor startup, and are presented in Table 3. No distinct dependence on reactor power can be determined since all the evaluated delayed gamma fractions are within the final uncertainty.

Figure 5: Evaluation of the delayed gamma signal fraction for both MIC and PTW IC at steps with different steady reactor power.

(a) Relative delayed gamma signal contribution from MFC (MP17) & MIC (MP25) measurements
(b) Relative delayed gamma signal contribution from MFC (MP17) & PTW IC (F25) measurements.
Table 3: Table of parameters $A$ and evaluated delayed gamma fractions after 10 min after reactor start-up for MIC & MFC and PTW IC & MFC combinations. End result calculated using a weighted average, where $\sigma^{-2}$ are taken as weights.

<table>
<thead>
<tr>
<th>Reactor Power</th>
<th>$A_{MIC}$</th>
<th>$S_{rel,MIC}$ @ 10 min</th>
<th>$A_{PTWIC}$</th>
<th>$S_{rel,PTWIC}$ @ 10 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 W</td>
<td>$1.18 \times 10^{-2} \pm 1.79 \times 10^{-4}$</td>
<td>$4.18 \times 10^{-2} \pm 2.15 \times 10^{-4}$</td>
<td>$1.03 \times 10^{-2} \pm 3.95 \times 10^{-4}$</td>
<td>$1.42 \times 10^{-2} \pm 9.67 \times 10^{-2}$</td>
</tr>
<tr>
<td>500 W</td>
<td>$1.51 \times 10^{-2} \pm 4.13 \times 10^{-5}$</td>
<td>$2.70 \times 10^{-2} \pm 6.58 \times 10^{-5}$</td>
<td>$1.00 \times 10^{-2} \pm 1.55 \times 10^{-5}$</td>
<td>$1.65 \times 10^{-2} \pm 4.70 \times 10^{-2}$</td>
</tr>
<tr>
<td>5 kW</td>
<td>$1.45 \times 10^{-1} \pm 3.31 \times 10^{-5}$</td>
<td>$2.75 \times 10^{-1} \pm 5.77 \times 10^{-5}$</td>
<td>$9.65 \times 10^{-2} \pm 1.15 \times 10^{-5}$</td>
<td>$1.84 \times 10^{-1} \pm 3.28 \times 10^{-2}$</td>
</tr>
<tr>
<td>10 kW</td>
<td>$1.56 \times 10^{-1} \pm 1.17 \times 10^{-5}$</td>
<td>$2.42 \times 10^{-1} \pm 3.8 \times 10^{-5}$</td>
<td>$9.90 \times 10^{-2} \pm 3.08 \times 10^{-4}$</td>
<td>$1.63 \times 10^{-1} \pm 3.18 \times 10^{-2}$</td>
</tr>
<tr>
<td>50 kW</td>
<td>$1.60 \times 10^{-2} \pm 7.12 \times 10^{-5}$</td>
<td>$2.03 \times 10^{-2} \pm 5.21 \times 10^{-5}$</td>
<td>$9.70 \times 10^{-2} \pm 4.12 \times 10^{-4}$</td>
<td>$1.72 \times 10^{-2} \pm 3.12 \times 10^{-2}$</td>
</tr>
<tr>
<td>End Result</td>
<td>$1.55 \times 10^{-1} \pm 1.07 \times 10^{-5}$</td>
<td>$2.42 \times 10^{-1} \pm 2.81 \times 10^{-5}$</td>
<td>$9.82 \times 10^{-2} \pm 9.24 \times 10^{-5}$</td>
<td>$1.71 \times 10^{-1} \pm 1.69 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

4.2 Delayed gamma fraction dependence on distance from core center

In figure 6 delayed gamma fractions are evaluated at 5 kW reactor power are evaluated with MIC being in different MP positions, and PTW IC inserted into F25 position, serving as a reference and MFC in MP17 as a neutron detector. In Figure 5 we observe a decrease of the delayed gamma fraction with increasing distance from the core center, while delayed gamma fractions from the PTW IC in Figure 6 agree with the evaluations in Table 3. Delayed gamma fractions and $A$ scaling factors for different positions of the MIC at 10 min after reactor startup are presented in Table 2. A linear fit of the parameter $A$ and delayed gamma fraction dependence on distance from core center is presented in Figure 7.

(a) Comparison of relative delayed gamma signal from MFC & PTW IC measurement with their MFC & MIC measurements. For different MIC positions, showing relative delayed gamma levels with increasing distance from core center.

(b) Relative delayed gamma signal contribution from MFC & PTW IC measurement for different MIC positions, showing repeatability within the uncertainties.

Figure 6: Evaluation of the delayed gamma signal fraction for both MIC and PTW IC, with MIC being inserted into various MP positions, and PTW IC serving as a reference in F25 irradiation position.

5 Conclusions and Outlook

We have demonstrated a novel approach in determining the delayed gamma signal from neutron and gamma flux measurements. Compared to previous work, this methodology provides the delayed gamma determination is provided for the entire time step, not only after rapid reactor shutdown. In order to discriminate the detector noise from reactor transients and for convergence of parameters $A$ and afterwards scaling the delayed gamma
Table 4: Table of parameters $A$ for MIC and evaluated fraction of delayed gamma rays after 10 min after steady reactor power is reached, in different irradiation positions @ 5 kW reactor power.

<table>
<thead>
<tr>
<th>MIC Position</th>
<th>Distance from center</th>
<th>$A$</th>
<th>$S_{\gamma,D,0,\text{MIC}}$ @ 10 min</th>
</tr>
</thead>
<tbody>
<tr>
<td>MP25</td>
<td>5.2 cm</td>
<td>$1.48 \times 10^{-3} \pm 3.31 \times 10^{-5}$</td>
<td>$2.75 \times 10^{-1} \pm 4.80 \times 10^{-2}$</td>
</tr>
<tr>
<td>MP21</td>
<td>10.4 cm</td>
<td>$1.22 \times 10^{-1} \pm 3.45 \times 10^{-4}$</td>
<td>$2.56 \times 10^{-1} \pm 4.07 \times 10^{-2}$</td>
</tr>
<tr>
<td>MP22</td>
<td>13.2 cm</td>
<td>$9.83 \times 10^{-7} \pm 2.79 \times 10^{-5}$</td>
<td>$2.32 \times 10^{-1} \pm 3.43 \times 10^{-2}$</td>
</tr>
<tr>
<td>MP23</td>
<td>18.3 cm</td>
<td>$5.29 \times 10^{-7} \pm 5.22 \times 10^{-5}$</td>
<td>$1.98 \times 10^{-1} \pm 2.88 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Figure 7: Radial dependence of parameter $A$ and delayed gamma fraction after 10 min after reaching steady reactor power with linear regression fit.

signal appropriately, we found it necessary to have high rate simultaneous signal acquisition from all detectors. The acquisition rate also determines the isotope decay times, which will be visible as delayed gamma. Therefore an increase in the sensor readout rate would improve the methodology.

The choice of appropriate detectors is also of great importance, as we can see at PTW IC measurements at 50 kW reactor power, where the sensitivity drops due to the temperature increase inside the F25 irradiation channel, which we did not expect. In the future such detector will either be used at lower power or replaced for a sealed ionization chamber.

The delayed gamma contribution to the total gamma flux does not scale with reactor power in the low power regime, without temperature feedback effects. It is however interesting to observe radial dependence of the delayed gamma flux contribution to the total gamma flux.

The next step is to apply a computational methodology for delayed gamma transport to the JSI TRIGA model and to replicate the power steps described in this paper computationally. This work is currently ongoing using the JSIR2S code, which has thus far been successfully validated on a fusion computational benchmark, and would be the first R2S methodology code applied to a fission problem.
References


