ABSTRACT

The JSI TRIGA reactor has several sample irradiation facilities with well characterized neutron fields by both simulations and measurements data. Because of this, JSI TRIGA has become a reference center for neutron irradiation of detector for ATLAS experiment (CERN). However, γ-ray characterization of irradiation facilities is yet to be performed. Monte Carlo γ-ray characterizations up to date have accounted for prompt γ-rays, neglecting delayed γ-contribution. Measurements suggest that delayed γ-rays may contribute to up to 30% of total γ flux, and is the only contribution of γ-rays after reactor shutdown. Initial steps in accounting for delayed γ-rays using R2S method have been performed and described in this paper. A rigorous two-step method (R2S) described here utilizes Monte Carlo particle transport code MCNP 6.1 for particle transport part of the problem, and FISPACT-II for neutron activation and delayed γ-ray generation, and custom Python scripts, joining the two codes. An example on the use of code is presented, in terms of evaluation on utilization of activated nuclear fuel as a viable γ-ray source in sample irradiation. For this example, fresh nuclear fuel is considered and a silicon pipe sample modeled in the computational model. Two nuclear fuel activation time regimes were simulated, short (several hours) and long term (in terms of 1 MWd and 10 MWd fuel burn-up).

1 INTRODUCTION

The Jožef Stefan Institute (IJS) TRIGA reactor is a 250 kW pool type reactor featuring numerous irradiation facilities with different characteristics in terms of size and neutron field properties [1]. Due to good neutron characterization, both computationally [1] and with measurements [2], the reactor has become a reference facility for neutron irradiation of ATLAS experiment (CERN) detectors [3]. Currently γ-characterization of the reactor is also being performed. Prompt γ-characterization is being performed using the Monte Carlo MCNP 6.1 code [4] with ENDF VII.0 [5] nuclear data libraries [6]. However these results are valid only for short irradiations on moderate to high power, as the measurements with ionization chamber indicate, that delayed γ-rays due to neutron activation contribute up to 30% of total γ-ray flux in steady state operation [7, 8, 9], and is the only source of γ rays after reactor shutdown. Thorough γ-ray characterization in terms of computational analysis and measurements in an operational reactor and after reactor shutdown, for both prompt and delayed

Delayed Gamma Ray Modeling Around Irradiated JSI TRIGA Fuel Element by R2S Method

Klemen Ambrožič
Jožef Stefan Institute Jamova cesta 39
1000 Ljubljana, Slovenia
klemen.ambrozic@ijs.si

Luka Snoj
Jožef Stefan Institute Jamova cesta 39
1000 Ljubljana, Slovenia
luka.snoj@ijs.si
γ-rays is planned in the near future. Initial steps in modeling the delayed γ-ray contributions from activated nuclear fuel, due to the fact that it can be a viable γ-ray source and is a main contributor of delayed γ-rays, have been taken, and methods and results described in this paper.


2 RIGOROUS TWO-STEP METHOD (R2S)

An R2S method [11] in reactor physics is a method of coupling particle transport capabilities with neutron activation analysis and delayed γ-ray generation. The basic idea is to divide the problem geometry into small voxels and calculate neutron spectra and total neutron flux values in each of them, or even subdivide the voxel to conform with geometry (cell-under-voxel approach) [12] by the means of a Monte Carlo neutron transport. Voxel neutron flux and spectrum, along with voxel material composition and mass is used in neutron activation analysis calculation, generating time dependent isotope inventory and delayed γ-ray spectra and intensities respectively. The latter results are used in a Monte Carlo photon transport as time dependent γ sources of delayed γ in a respective voxel for delayed photon field, spectrum, kerma and dose particle transport calculations.

3 COMPUTATIONAL SETUP

Figure 1: Schematic of the JSI TRIGA Mark II reactor, side (left) and top (right) view.

JSI TRIGA is a pool type reactor, with maximum steady state power of 250 kW (Fig. 1). The fuel elements are arranged in an annular configuration into rings A-F (Fig. 2). A detailed JSI TRIGA reactor MCNP model, based on the criticality benchmark model [13], which has been thoroughly validated by multiple experiments [14, 15, 16], was used for total neutron flux and spectra distribution inside the fissionable material part of the fuel element (U-ZrH fuel meat) of several standard JSI TRIGA fuel elements (12 wt% uranium, enrichment 20 %). Neutron activation for fresh fuel meat (U-ZrH) only was calculated, as it is the main contributor of delayed γ-rays. Kerma in sample was calculated using voxel volume averaged energy deposition estimators, and the dose was calculated using ICRP-21 [17] flux to dose conversion factors for photons. Fuel isotopic
compositions, as well as major isotopes, contributing to the dose on the sample were also calculated. Each of the core ring fuel element representatives fuel meat was divided in 10 axial × 5 radial × 5 azimuthal voxels, and a 100-group neutron spectra and total flux values for steady state operation were calculated in each of them. An irradiation plan in terms of reactor power and duration for the whole core, along with voxel calculated neutron spectra, fluxes and material compositions was used to construct neutron activation code FISPACT-II input files for each voxel respectively. After the calculations for all the voxels were performed, a Python script was used, to merge the output calculations data accordingly and construct MCNP γ sources for each stage of neutron irradiation or shutdown. A flow-chart of the procedure is depicted in Fig. 4. Two irradiation time regimes were simulated: short-term irradiation, where reactor operated for a few hours, and long-term irradiation, where a typical 40 h/w operation at full reactor power was simulated until a burn-up of 1 MWd or 10 MWd was achieved.

As the gamma irradiation in the JSI TRIGA reactor is performed mostly to study radiation hardness of Si based semiconductors, the main motivation of this work is to use the R2S method to calculate kerma and dose on Si. For this purpose a cylindrical pipe silicon sample was modeled around the activated fuel element, with kerma and dose distributions calculated in it (Fig. 5).
4 RESULTS

In this section, an overview on the results for both short-term and long-term irradiations using the above mentioned R2S approach on will be presented. Activities of fuel elements, dose and kerma rates on the silicon sample are given in this section. Fuel elements inside the JSI TRIGA reactor are arranged in concentric rings. A single element from each ring was selected for calculations (Fig. 4).

4.1 Short activation

A short fuel activation of several hours is considered in this case. This corresponds to day to day operations, where reactor is operational for several hours at full reactor power. Fresh nuclear fuel prior to irradiation is considered. Kerma-rate and dose-rate results are given in terms of kerma and dose-rate range on the sample, due to their distribution in the silicon sample, with maximal values being in the most inner part at center height of the sample, and lowest values at the sample outer edges. All of the results have a computational uncertainty below 1%.

(a) B2 fuel element activity.

(b) E5 fuel element activity.
Figure 6: Two representative fuel elements (B2 and E5), with different activation times. X-axis denotes time after the irradiation.

(a) B2 fuel element $\gamma$-ray spectra after 1 h and 20 h of operation at full reactor power.

(b) Isotope contributions to the contact dose in B2 element, after 20 h of operation at full reactor power.

Figure 7

Spectra of $\gamma$ rays for each voxel element are calculated during the neutron activation calculation procedure, to enable us to produce sources of delayed $\gamma$-rays respectively. An integral spectrum can also be calculated (Fig. 7a). In addition, isotope contribution to contact dose is also calculated, which gives insight on radiation hazards due to neutron activation of components in a nuclear facility (Fig. 7b).
4.2 Long activation

For long term activations, a 40 h/w operation at full power is considered, until a burnup of 1 MWd or 10 MWd is achieved, starting with fresh fuel. Fuel element activity, kerma-rate and dose-rate to the silicon sample after reactor shutdown are calculated. 

$\gamma$-ray spectra emitted by activated voxels have again been summed in terms of fuel element $\gamma$-ray spectra (Fig. 9a) as a whole, and isotopic contribution to contact dose have been calculated (Fig. 9b).

Figure 8: Results for representative fuel elements with burn-up of 1 MWd and 10 MWd.
4.3 Results comment

γ-decaying isotopes in the nuclear fuel are mainly produced in nuclear fission, and their distribution is proportional to fission rates and therefore to power distribution. The differences in the γ-activities of fuel elements irradiated for same periods of time are therefore attributed to power distribution which has been calculated per fuel element \[^{[13]}\]. The ranges of kerma-rates and dose-rates can be attributed to the axial neutron flux distributions, which has also been evaluated both computationally and by measurements \[^{[2]}\].

For longer irradiation times, or until a desired burn-up is achieved, we can clearly observe the effect of increased neutron flux distribution in inner elements. The γ-decaying isotope production rate is again proportional to neutron flux, and with shorter irradiation time, fewer of the so produced isotopes have decayed up to the irradiation end. This affects the isotopes, which reach saturation in several hours, which can are visible in the Fig. 8 with differences between fuel elements for same burn-up. With the increased burn-up, long-lived isotopes are produced linearly with the increased irradiation time and burn-up, therefore the \(10 \times\) increase in activities and sample dose-rates and kerma-rates at 10 MWd burn-up, compared to the 1 MWd.

5 SUMMARY

The R2S method presented here aims to provide preliminary analysis on contribution of delayed γ-rays to photon kerma and dose-rates in the reactor irradiation facilities. Initial measurement of delayed γ-ray dose in the vicinity of several fuel elements show agreement with the calculations. The codes and scripts developed for this problem specific calculation procedure give valuable insight on developing a generalized method for R2S calculations, with possible ”geometry under voxel” approach implemented \[^{[12]}\], while current method performs division, conforming to model geometry. The model segmentation, neutron flux and spectrum calculations, as well as neutron activation and delayed γ-ray source generation would be performed automatically. The code would be used for delayed γ-field characterization of the JSI TRIGA reactor, which would increase utilization for γ-ray radiation hardness studies.

R2S methods are applied almost exclusively to fusion devices, where little to no utilization on fission reactors. In the following months, the method will be applied to the whole JSI TRIGA reactor core, along with the development of the above mentioned generalized R2S code and with γ field measurements in the JSI TRIGA reactor during reactor operation and after reactor shutdown. The
measurements will serve to establish measurement procedures of $\gamma$ measurements in mixed $\gamma$-neutron fields and to validate the computational results. The current and a generalized method will be used in the future to evaluate component activation inside nuclear power plants, as well as for accurate classification of nuclear waste after nuclear facility’s decommissioning, therefore increasing long-term storage facility utilization.

REFERENCES


