Gamma and neutron source term calculation for irradiated TRIGA Mark II fuel using ORIGEN2

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Abstract. TRIGA Mark II has served as nuclear research reactor for decades, which is to provide research facility towards nuclear development as well as for trainings in the aspect of education and industry. Standard TRIGA fuel, UZrH\textsubscript{1.6} is used in this reactor which can be found in two types; aluminium or stainless steel cladding. In this study, stainless steel cladded fuel used in Reactor TRIGA PUSPATI (RTP) that consists of fissile U-235 with 19.9\% enrichment and 20\% weight of Uranium is used as reference for input data. The irradiated fuel inventories and fuel burnup were determined using ORIGEN2 code by referring to PWR data library, consists of gamma and neutron source term comes from activation products, actinides and fission products after 18 years of irradiation and 5 years of cooling period with 200 days of time step. The outcomes from this study can be concluded with the inventories from fission products to be the highest in all categories, in which the U-235 depleted up to 52.9\%. The results from this simulation is crucial as it is then carried forward for radiation shielding for interim storage facility.

1.0 Introduction
TRIGA Mark II research reactor was installed at Malaysian Nuclear Agency in the year of 1982, named as Reactor TRIGA PUSPATI (RTP) and went critical for the first time on 28 June of the same year with excess reactivity of $0.15$ [1]. RTP is the one and only research reactor available in Malaysia and it has been operating for 37 years with maximum thermal power output of 1 MW. The core consists of standard TRIGA fuel UZrH\textsubscript{1.6} which is a mixed of 8.5, 12, and 20 wt\% of uranium content with 19.9\% enrichment of U-235. All the fuels are stainless-steel cladded (type-104). Through its operation years, RTP core have been reshuffled for few times in order to utilize the fuel to control the criticality of the core. As in the year 2017, the core operates with its latest 15\textsuperscript{th} configuration of fuel assembly as shown in Figure 1 where the fuels together with control rods and dummy elements are arranged in all seven circular rings.
In this work, source term estimation in terms of neutron and gamma of irradiated fuel was simulated by using ORIGEN2 by taking the data of fresh 20 wt% uranium content fuel in RTP as the target of reference. The use of ORIGEN2 is based on its capability to calculate buildup, decay and processing of various selection of radioactive material. This paper describes the methods used in order to get the fuel burnup, photon spectrum and also the neutron source of a single fuel after irradiation.

2.0 Fuel element source term estimation

The estimation was made based on the theoretical limit for U-235 depletion in TRIGA fuel that is around 25% to 50% reduced from its original value, and therefore leads into the situation where the fuel should be removed out from reactor operation [2]. For the burnup calculation, few assumptions were made as initial conditions. Since the ORIGEN2 code simulates for one fuel assembly only, an average power for one fuel is required to be determined. The TRIGA reactor is fixed to produce 1 MW thermal power in the first six years and reduced to 750 kW for the rest of irradiation period.

A comparison was made by referring to the irradiation history of RTP during its first criticality in which the situation of 66 fuels of 8.5 wt% fuels is substituted with 20 wt% fuels in the core to produce 1 MW thermal power. Thus, a total of 23 fuels of 20 wt% uranium content fuel is determined to be in the hypothetical core, with an average power of 0.04348 MW (1 MW) and 0.032607 MW (750 kW) is produced in one fuel.

The total irradiation time is one of the variable in this work, which is depending to the output where the depletion limit of U-235 is reached. Considering the total of six hours operation per day, five days a week, the total time were then standardized according to unit day with 200 days of time step. The fuel is also allowed to cool, assuming the period of decay within 5 years to be considered, where the output data were distinguished for every 300 days interval.

Figure 1. The Core-15 configuration, the latest configuration of RTP core [1].
There are several libraries to choose from, but for this work, the cross section libraries for PWR is used which correspond to the irradiation power command (IRP). The libraries are identified by NLIB numbers, which for PWR case, NLIB=204 (activation products), NLIB=205 (actinides) and NLIB=206 (fission products) are used, and thus, resulting three separate and distinct nuclide lists as the output. Photon data yield library also included, which gives the photon per disintegration in eighteen energy groups. The data of fuel includes the weight and atomic mass for every isotopes in fuel meat (active region in the fuel where energy is produced by fission process) and cladding materials which are as shown in Table 1 and Table 2.

Table 1. Composition of fuel meat of TRIGA fuel.

| Isotope | Mass (g) |
|---------|----------|
| U-235   | 99       |
| U-238   | 396      |
| Zr      | 1955.38  |
| H       | 34.57    |

Table 2. Composition of cladding for SS-clad TRIGA reactor fuel.

| Isotope | Mass (g) |
|---------|----------|
| C       | 0.66     |
| N       | 1.07     |
| Si      | 8.19     |
| P       | 0.37     |
| S       | 0.25     |
| Cr      | 155.69   |
| Mn      | 16.39    |
| Fe      | 564.12   |
| Co      | 0.66     |
| Ni      | 73.09    |

The composition data for the cladding materials were taken by varying the total composition used in the ORIGEN2 run for TRIGA reactor with SS-clad fuel. These composition were described which is by referring to midrange burnup of 19,492 MWd/MTHM, that equates to 3.8 MWd for a fuel element after irradiated for 3.469 years at a constant power of 0.003 MW [3].

3.0 Results and discussions

3.1 Burnup calculation

Burnup calculation were performed as it is one of the outputs provided in ORIGEN2 together with the summarized information of fluxes, specific power and infinite multiplication factor data for the simulation, at which the core being operated at 1 MW (for the first six years) and 750 kW (the rest of the operation period). After cessation of fuel irradiation (continuous 1200 days of operation), the results obtained regarding burnup of individual TRIGA fuel is as shown in Table 3. The mass of U-235 in the irradiated fuel is 52.9% depleted from its original value.
Table 3. Burnup data of the irradiated TRIGA fuel.

| Average power produced by one fuel | 0.0362319 MW |
|-----------------------------------|-------------|
| Fuel burnup                       | 43.4782 MWd |
| Average neutron flux              | 1.26E+14 n/cm^2.s |
| $K_{inf}$                         | 1.28430     |

The irradiation was stopped after continuous 1200 days (18 years) of operation as the depletion limit is reached. This action was taken by referring to the change of mass of U-235 in the fuel, in the same time the mass of U-238 was ensured to have no significant change in its value as it is supposed to experience scattering with fast neutron, which resemble the realistic fission process occur in RTP. The relevance of this results were referred to the study done by Rabir (2017) which showing the change of the mass of major radioisotope mass over its burnup value in an irradiated TRIGA fuel [1]. Another action was taken with the aim to ensure the output’s reliability, which is by comparing them with a data of nuclear mass inventories of spent research reactor fuel assemblies, which applied the use of ORIGEN and WIMS code in determining irradiated fuel inventories, including TRIGA type (specifically for 20wt% uranium content fuel). The comparison can be referred in Table 4.

Table 4. Comparison between the mass results obtained for RTP fuel and data of TRIGA in [4].

| Criteria          | Results based on RTP TRIGA fuel | Data of TRIGA fuel provided in [4] |
|-------------------|---------------------------------|-----------------------------------|
|                   | Before irradiation | After irradiation | Before irradiation | After irradiation |
| Mass of U-235     | 99 g               | 46.65 g           | 98 g               | 45.65             |
| Mass of U-238     | 396 g              | 390.8 g           | 392 g              | 383.5 g           |

3.2 Gamma and neutron source term calculation
The neutron production rate simulated from ORIGEN2 are relatively compact and straightforward, which consists of neutron production rate from (alpha, n) reactions and spontaneous fission for each radioisotope involved. The results are as shown in Figure 2 and Figure 3, where a comparison was made between the values after irradiation ends and after 5 years of cooling.

Table 5. Summary of total neutron production rate.

| Neutron source      | Total neutron production rate (neutron/second) |
|---------------------|-----------------------------------------------|
|                     | After irradiation | After 5 years of cooling                      |
| (alpha, n) reaction | 6.61E+03          | 1.50E+03                                      |
| Spontaneous fission | 3.07E+04          | 4.54E+03                                      |
As for photon emission rate, the output data were separated into three segments according to the type of radioisotopes. The activation products includes the low proton number (Z) and radioisotopes that is a product from structural materials of the fuel. The actinides includes heavy isotopes and their daughters, and finally the fission products that includes a significant fission product yield. Gamma energy and the change of gamma emission rate from the point of irradiation ends and after 5 years of cooling for all activation products, actinides, and fission products for eighteen groups of gamma are as shown in Figure 4, Figure 5, and Figure 6. The summary of the total photo emission rate from all 18 energy groups as shown in Table 6.

**Table 6. Summary table of the total photo emission rate from all 18 energy groups.**

| Type of radioisotope | Total photo emission rate from all 18 energy groups (photon/second) |
|----------------------|--------------------------------------------------------------|
|                      | After irradiation | After 5 years of cooling |
| Activation products  | 2.460E+13         | 1.516E+06               |
| Actinides            | 2.513E+14         | 1.257E+10               |
| Fission products     | 1.301E+15         | 1.519E+13               |
Figure 4. Photon emission rate from activation products.

Figure 5. Photon emission rate from actinides.
From the results above, it can be seen that radioisotope from fission products to be the main contributor the photon emission rate compared to other two, followed by actinides in both after irradiation and after 5 years of cooling. This is probably because of the longer half-life radioisotopes which emits gamma in fission products that can be significantly found, such as Cs-137 ($t_{1/2}=30.17$ years). As for activation products, the radioisotopes involved are mainly those produced from the structural material (cladding) which have shorter half-life, and this can be seen from the drastic change of photon emission rate in activation products after irradiation until after 5 years the fuel allowed to cool down and decay.

4.0 Conclusion
The results of the gamma and neutron source term from irradiated TRIGA Mark II fuel were calculated using ORIGEN2, which resulting fission products to emits highest value of photon emission rate. The source of neutron can be found from two; (alpha, n) reaction and spontaneous fission occurs inside of the irradiated fuel in both event; after irradiation and after 5 years of cooling, with the total of $3.73E+04$ neutron/second and $6.04E+03$ neutron/second respectively. This work is done based on the photon and PWR data libraries on 20 wt% uranium content fuel only. The data provided are respected to one fuel assembly only. This results can be used as the reference for further studies involving fuel inventories of TRIGA fuel, such as to estimate surface dose calculation on interim storage for TRIGA spent nuclear fuel.

References
[1] Rabir M H B, Zin M R B M, Karim J B A, Bayar A M B J, Usang M D A, Mustafa M K A B, Jalil M H B 2017 Neutronics calculation of RTP core AIP Conf. Proc. 1799.
[2] International Atomic Energy Agency 2013 Management and storage of research reactor spent nuclear fuel: proceedings of a technical meeting held in Thurso, United Kingdom. (Vienna: International Atomic Energy Agency) ISBN 978-92-0-138210-8.
[3] Sterbentz J W 1997 Radionuclide mass inventory, activity, decay heat, and dose rate parametric data for TRIGA spent nuclear fuels INEL-96/0482 (Idaho Falls, Idaho: Lockheed Martin Idaho Technologies Company, Idaho National Engineering and Environmental Laboratory).

[4] Pond R B, Mato J E 2000 Nuclear mass inventory, photon dose rate and thermal decay heat of spent research reactor fuel assemblies rev. 2 ((United States: Argonne National Lab.(ANL), Argonne, IL) ANL/RERTR/TM-26).