Demonstration of Decay Heat Calculations using the MCNP-ORIGEN Activation Automation Tool

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Abstract

This work targets mainly experiment safety analyses for research nuclear reactors. The safety analyses evince that accidents do not undermine the experiment integrity, which could lead to a radioactive material release. After a reactor shutdown, the radioactive materials continue to decay and release energy. Nuclear safety analyses require the estimation of this released energy. The accurate assessment of this released energy allows to better determine the heat removal requirements and ensure the effective experiment cooldown. The main objective of this summary is to introduce a module capable of calculating the heat production in an experiment due to decay heating. For the calculation, the module relies on the MCNP-ORIGEN Activation Automation (MOAA) tool. This paper introduces the decay heat calculation module, explains its workflow, and showcases its capabilities by conducting a simple nuclear engineering exercise.

Keywords: safety, decay, heat, MCNP, ORIGEN, MOAA.

1   Introduction

Nuclear research reactors enable a vast range of uses and purposes, including scientific research, material testing, and production of radioactive materials. Within radioactive material production, we distinguish three main applications: neutron activation analysis, neutron transmutation doping, and radioisotope production for medicine. Neutron activation analysis facilitates the measurement of minute quantities of an element in a sample. Neutron transmutation doping changes silicon properties, making it highly conductive. The electronics industry highly benefits from this application for chips production. Finally, the medical field utilizes radioisotopes for diagnosing and treating health conditions like cancer and cardiovascular diseases. For

example, technetium-99m comes from the decay of molybdenum-99, and its primary use is diagnostic imaging [1]. In this work, we refer to the devices utilized in any of the aforementioned research reactor applications as experimental devices or just experiments.

This work targets mainly experiment safety analyses. Research reactor safety analyses demonstrate that experiments do not compromise the safe operation of a reactor. The safety analyses evince that accidents do not undermine the experiment integrity, which could lead to a radioactive material release. In an operating reactor, there is an equilibrium between the generated and removed heat, and the successful experiment heat removal prevents any overheating damage. After a reactor shutdown, the radioactive materials continue to decay and release energy. Nuclear safety analyses require the estimation of this released energy. Previous work [2][3] has studied the experiment's integrity during a loss-of-coolant accident utilizing pre-defined decay heat values. However, an accurate assessment of this released energy allows to better determine the heat removal requirements and ensure the effective experiment cool down.

The main objective of this summary is to introduce a module capable of calculating the heat production in an experiment due to decay heating. For the calculation, the module relies on the MCNP-ORIGEN Activation Automation (MOAA) tool [4]. It works as an external module, and it may or may not be integrated into MOAA in the future. This paper introduces the decay heat calculation module, explains its workflow, and showcases its capabilities by conducting a simple nuclear engineering exercise.

2   Methods

The decay heat calculation module relies primarily on MOAA. MOAA is an activation analysis tool that calculates radionuclide activity, mass, heat, delayed neutron, and prompt and delayed gamma signatures by coupling MCNP [5] to ORIGEN [6].

MCNP is a general-purpose, continuous-energy, generalized-geometry, Monte Carlo radiation-transport tool that can track neutrons, photons, electrons, and other particles. It is developed by the Los Alamos National Laboratory and was first released in 1983. ORIGEN is a general-purpose point depletion and decay tool, it is developed by the Oak Ridge National Laboratory, and it has been available since 1980. ORIGEN is integrated into the SCALE Code System, which is a modelling and simulation suite for nuclear safety analysis and design [6]. Additionally, MOAA uses other SCALE modules as well: COUPLE and OPUS. ORIGEN requires a single space and spectrum-weighted cross-section library, that the user can generate using COUPLE. The OPUS module extracts specific data from the ORIGEN output libraries and generates data for post-calculation analysis.

Figure 1 displays the decay heat calculation scheme. MOAA calculates the concentration of the radioactive isotopes contributing to the decay heat. MCNP obtains the geometry and material-dependent parameters of the user-defined system, such as flux data, spectra data, and reaction rates of interest. MOAA feeds the MCNP spectrum and reaction rates to COUPLE for calculating the one-group cross-sections.

Then, ORIGEN conducts the depletion calculations based on those cross-sections. For further information on the MOAA calculation scheme refer to [4].
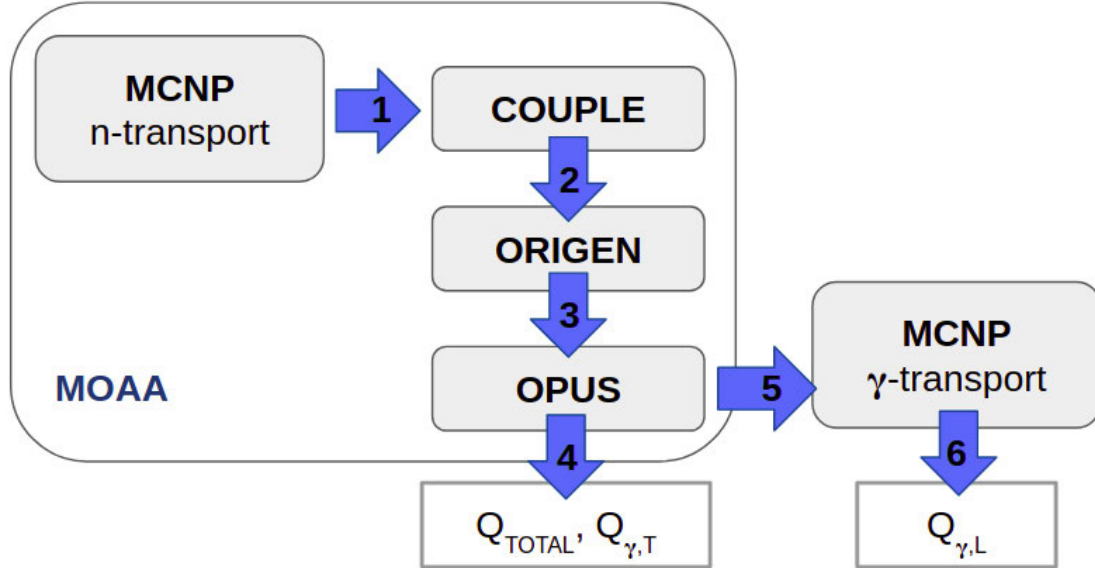

Figure 1: Decay heat calculation scheme.

Next, we calculate the heat production in the experiment using the following equation

$$Q_{decay}[W] = Q_{TOTAL} - Q_{\gamma,T} + Q_{\gamma,L} \qquad (1)$$

where Q_{decay} is the decay heat generated in the region of interest, Q_{TOTAL} the total decay heat, $Q_{\gamma,T}$ the total gamma heating, and $Q_{\gamma,L}$ the locally deposited energy by the gamma radiation.

ORIGEN calculates Q_{TOTAL} and $Q_{\gamma,T}$ assuming those to be locally deposited. While this assumption is valid for charged particles - e.g., alpha and beta particles, it is not for gamma radiation [7]. Hence, $Q_{\gamma,L}$ must be determined with a photon-transport calculation. OPUS extracts the gamma source distribution from the depletion calculation. Following, MCNP uses that distribution to define a fixed photon source, run the photon-transport calculations, and evaluate $Q_{\gamma,L}$.

3   Results

The present work demonstrates the decay heat module capabilities by displaying a simple exercise. A top view of the exercise geometry and its dimensions are shown in Figure 2. The fuel element and experiment heights are 14.8 and 24 cm, respectively. The experiment centre is located 8.2 cm away from the reactor centre. The reactor encompasses the following materials: 85% enriched uranium with a density of 19 g/cc for the fuel elements, light water with a density of 1 g/cc for the moderator, and aluminium with a density of 7.87 g/cc for the experiment.
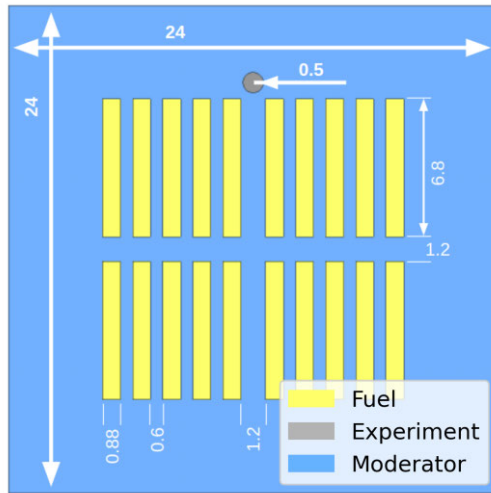
Figure 2: Model geometry.

The reactor operates at a constant power of 5 MW over a period of 50 days. After that period, the reactor shuts down, and the decay heat is calculated in 13 decay steps distributed as follows: one step immediately after shutdown (to avoid the prompt-gamma contributions, this step is taken 1 min after shutdown), two steps 20 min and 40 min after shutdown, and ten steps, each taken every hour. The materials considered to contribute to the decay heat are the fuel elements and the same experiment, whereas the moderator activation is neglected.

Figure 3 displays the heat production overtime in the experiment. The heat produced in the experiment immediately after shutdown is 42 W, which is less than 0.001% of the reactor total power. As expected, the heat production has a decaying shape. The curve has a half-life lower than 1 second, and after 4 seconds the heat production becomes smaller than 10 W.
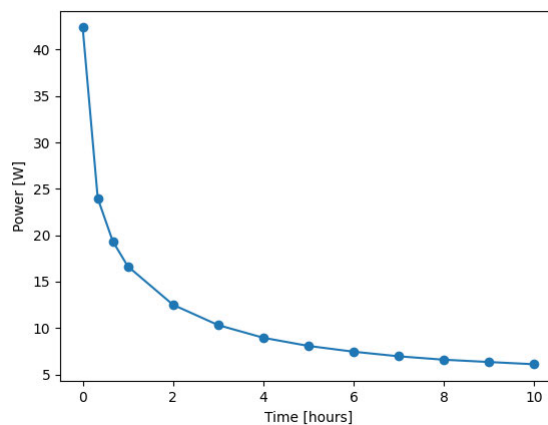

Figure 3: Experiment heat production over time in the demonstration exercise.

Figure 4 shows the heat contribution by each source. The figure displays the contributions for the first and the last decay steps. The fuel elements contribute to the

experiment heating via the deposition of the gamma radiation that originated in them. The experiment self-heating is a combination of the charged particles' energy deposition and the heat deposition of the gamma radiation originated in the same experiment. For both decay steps, the largest contribution to the heat deposition is originated in the closest fuel elements to the experiment. Finally, the experiment material is not considerably activated during the irradiation period and the self-heating contribution is deemed negligible.
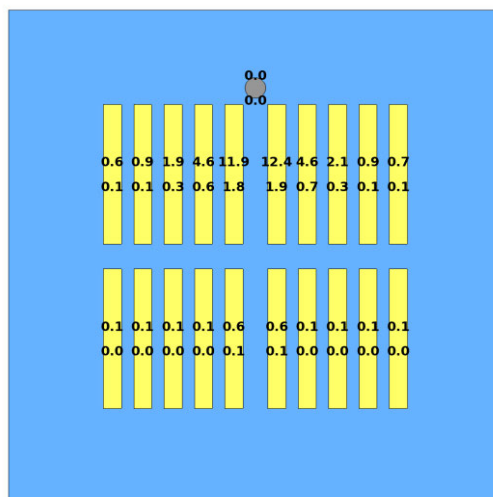

Figure 4: Heat contribution by each source for different decay steps. Above: Immediately after shutdown. Below: 10 hours after shutdown.

4   Conclusions and Contributions

The assessment of the decay heat after a reactor shutdown is necessary for nuclear safety analyses to ensure the effective reactor cool down. The determination of the decay heat allows for the computation of the heat source term for thermal-fluids calculations. Then, the thermal-fluids calculations determine the experiment cooling requirements to ensure that the experiment is not subject to overheating damage, which could lead to radioactive material release. This paper presents a decay heat calculation workflow to support the development of safety analyses for nuclear research reactor experiments.

This paper introduces the decay heat calculation scheme implemented as an external module for MOAA. MOAA calculates the nuclide concentration after depletion while OPUS outputs the emission of gammas from the radioactive isotopes contributing to the decay heat. Given that ORIGEN assumes the decay heat to be fully deposited locally, an MCNP photon-transport simulation is necessary for evaluating the gamma deposition in the experiment. MCNP uses OPUS information to define the photon source for that simulation.

The paper presents an exercise defined by a simple reactor geometry and its results to showcase the module's capabilities. The exercise results show that the heat production in the experiment is lower than 0.001% of the reactor total power for all

decay steps. Additionally, the results show that the largest contributors to the experiment heat production are the fuel elements closest to the experiment.

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