Fine mapping of the power density distribution of MTR fuel using gamma spectroscopy

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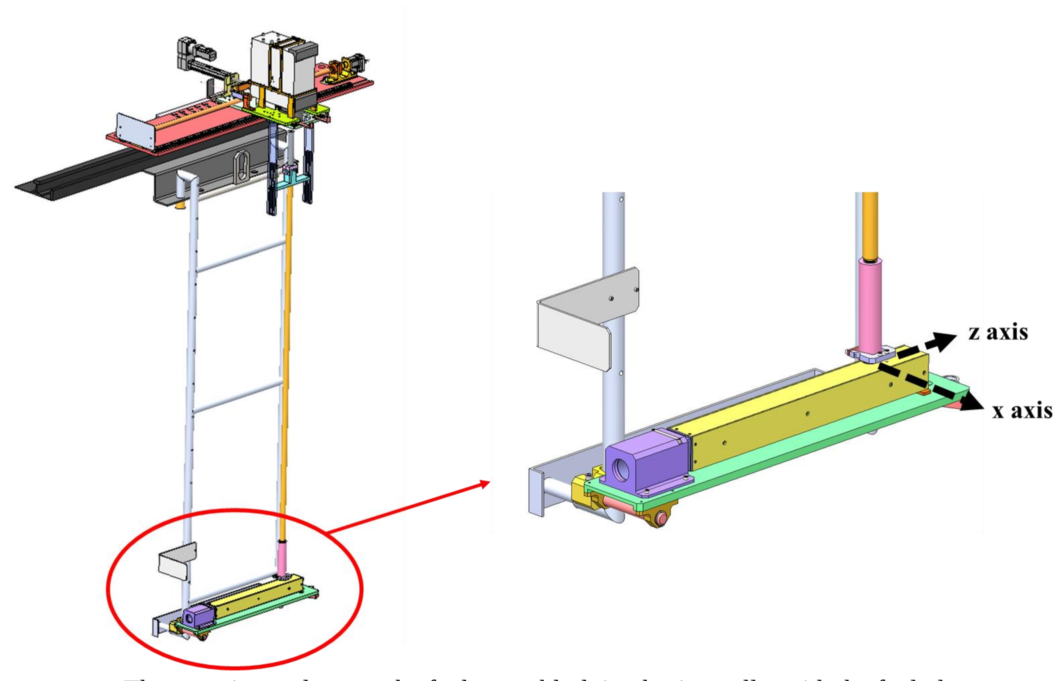
Abstract

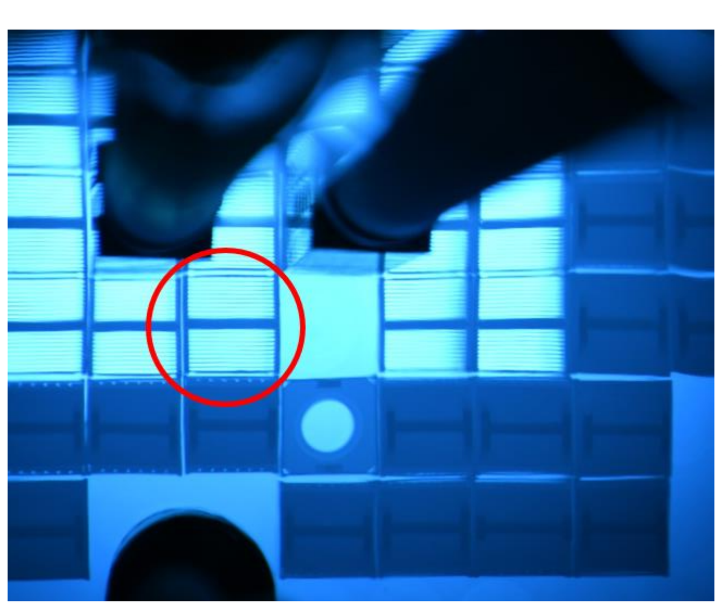
An accurate power-density distribution estimation is essential in planning, commissioning, and maintaining the operation of nuclear reactors. A flux trap such as a water volume in the core increases the thermal flux around it, and thus the power peaking factor (PPF) may rise, reducing safety margins. To predict the effect, high-resolution simulations are required, including local burnup calculations. Thus, experimental validation of computed PPF allows a better estimation of the calculation errors. Here we report measurements allowing fine 2D mapping of the surface power density in MTR fuel assemblies, analyzing fission products by gamma spectroscopy. We probed a fuel assembly positioned near a flux trap in the Israeli Research Reactor - 1 (IRR-1). We found a steep power density profile, indicating a need for a high tally resolution for correct prediction of this effect. However, the resulting PPF agreed well with full-core 3D Monte-Carlo simulation with homogeneous fuel-plate burnup assumption.

Experimental Description

- High-purity germanium spectroscopic gamma detector (model Falcon5000, Canberra) aligned with an air-filled collimator, positioned above a fuel assembly lying horizontally.
- The counts from fission products are proportional to the power density, can be used to measure the power density profile and PPF in a single fuel assembly.
- We used a motorized stage to scan the FA along the x-axis for several z values, with the fuel plates lying perpendicularly to the collimator.



The experimental setup: the fuel assembly lying horizontally, with the fuel plates perpendicular to the collimator. The latter leads to an HPGe detector.



Irradiation of the chosen FA (circled in red) inside the IRR-1 core

- Considerably depleted FA, with 20%-80% local depletion (depending on height along z axis).
- The FA was not irradiated in the past decade, no short-lived isotopes from past irradiations.
- 3 hour irradiation @5MW in the IRR-1 next to a vacant lattice cell in the core filled with water (which acts as the flux trap).

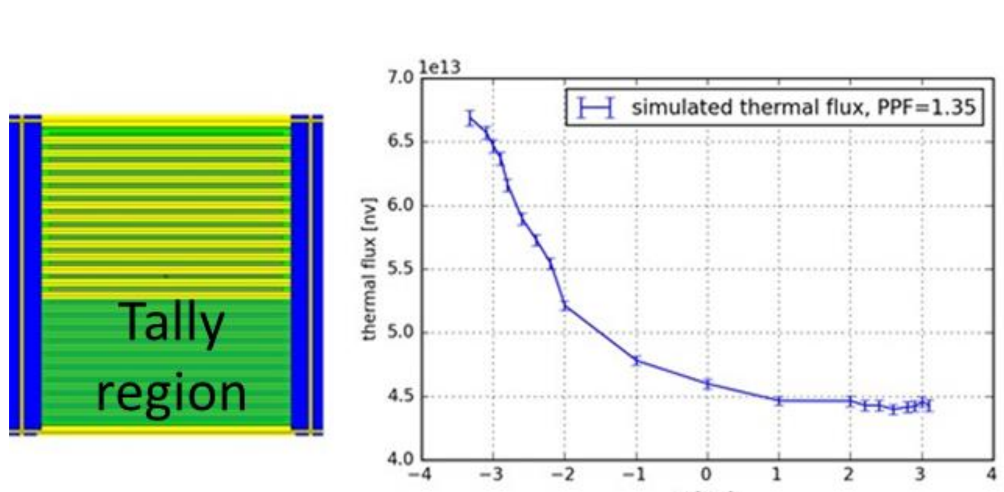
Preliminary Considerations

The analysis of this experiment relies on gamma rays from fission products:

- Cs-137, which has a half-life of $T_{1/2}$ ~30 years, is indicative of the whole irradiation history of the FA.
- Short-lived isotopes which originate from the irradiation of the fuel assembly next to the flux trap.

Properties of fission products used in this experiment

Radionuclide	Emission probability P_g	Energy $E\,[keV]$	Decay constant $\lambda\,[1/sec]$
Cs-137	0.850	662	7.31E-10
Ba/La-140	0.954 0.461	1596 487	6.29E-7
I-131	0.812	364	9.99e-7
Te/I-132	0.987	668	2.48E-6
Mo/Tc-99m	0.896	140	2.92E-6



Left: cross section of the tallied FA. Right: thermal flux in the FA irradiated next to the flux trap

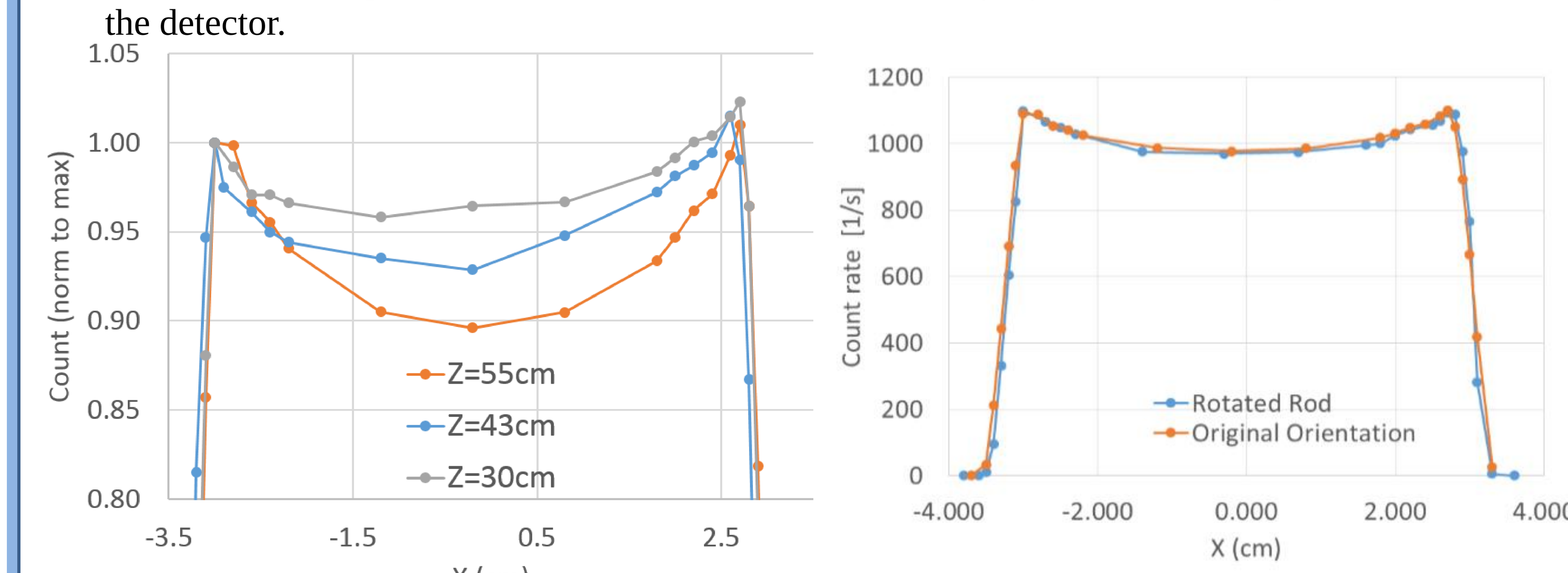
- Operation history of the IRR-1 reactor is modelled using MCNP coupled with DRAGON burnup module.
- Whole-core simulation of the FA irradiated next to the flux trap, thermal flux at the measured region is calculated.
- Simulated PPF=1.35.

Results

PRE-IRRADIATION: A preliminary measurement, focused on the count rate of the 662 keV emission line of the long-lived Cs-137 along the z axis as well as along the x axis. This allowed for:

- Calibration of the experimental setup against previous measurements.
- Obtaining the depletion distribution resulting from the irradiation history of the assembly.

Due to self-absorption, the measurement is affected mainly by the three fuel plates nearest to the detector.



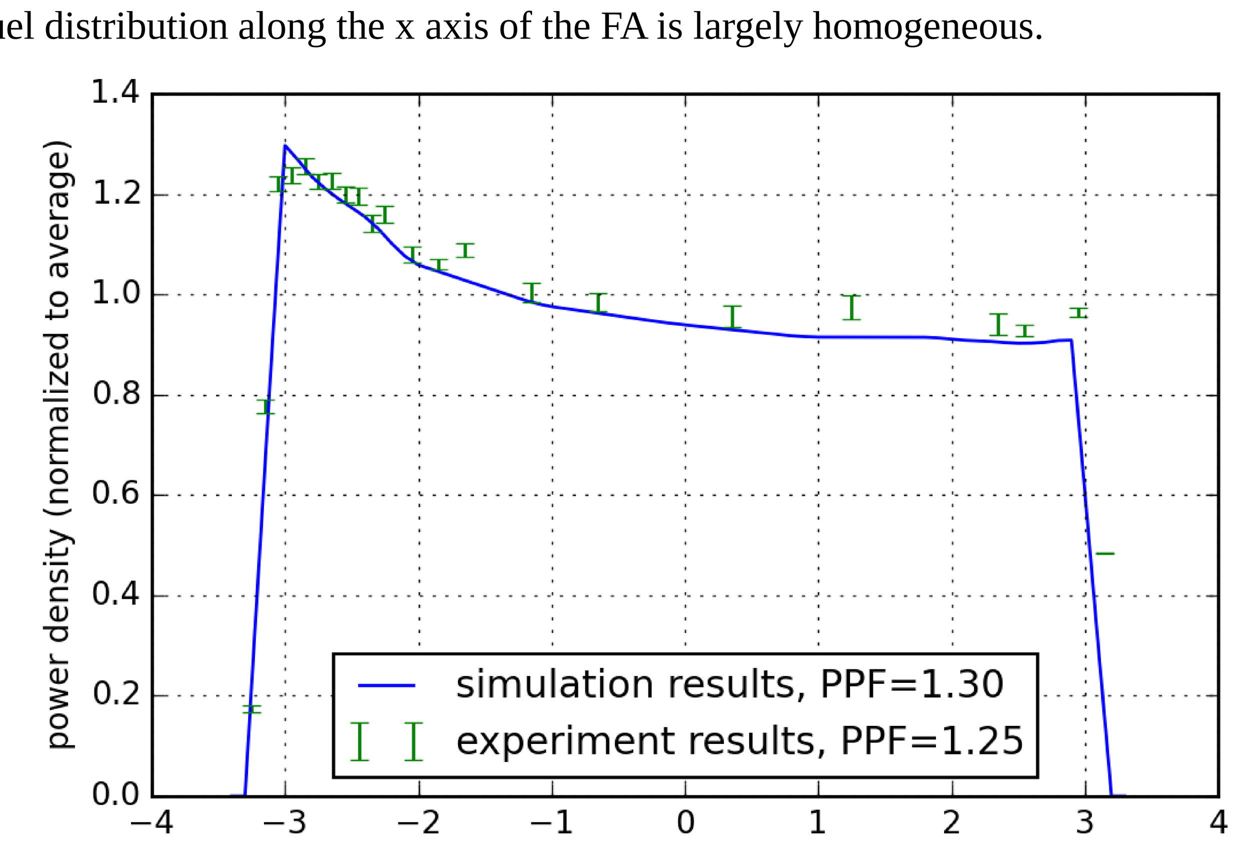
Preliminary measurement results. Left: lateral (x) scans at various heights along z direction, corresponding to different depletion values. Right: comparison between measurements from opposing sides of the FA, at z=55 cm.

- Largely homogeneous depletion inside the plate in the x axis, max-to-mean depletion of 1.1 at the most, for the least depleted cross-section z=55 cm.
- The depletion is symmetric around the center of the fuel plates and on both sides of the assembly, since the irradiation of the assembly was generally uniform throughout the history.

POST-IRRADIATION: The assembly was scanned along the x direction, 5 cm below the top of the fuel plate.

- The data from several short-lived isotopes were normalized, variance-weighted average was performed to decrease measurement errors.
- The resulting power profile is compared to the thermal flux simulation results, convolved with a 3 mm wide window function to simulate the effect of the collimator.

The measured power distribution fits well with the simulated thermal flux. This indicates that the fuel distribution along the x axis of the FA is largely homogeneous.



Comparison between the measured power density distribution and the simulated thermal flux distribution.

Conclusions

The results of our experiments validate the computational model of the IRR1, namely the assumption of homogeneous fuel distribution throughout the fuel plates' breadth. We conclude that our computational model is valid for the IRR-1, but for establishing the correct PPF, it is required to calculate the instantaneous flux in a high resolution. However, in the computation of cores which incorporate built-in flux traps, the depletion of the fuel assemblies which are adjacent to the water guide for the control blades should be treated more carefully. In such cases, our experimental method could be a useful tool to benchmark the calculations. In future iterations of this experiment, we intend to perform more measurements in various depletion levels (heights), and calibrate the detector efficiency such as to obtain absolute results of activity, rather than power or flux distributions relative to the average. Furthermore, an independent measurement of the thermal flux along the plates (using activation analysis), can be combined with the power distribution measurement to derive the fuel distribution along the fuel plates.

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