

Gamma heating calculations for the HFR

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Abstract

In the design of an irradiation experiment one needs to know the amount of heat generated in it. When photons are the main source of heating, as is the case in experimental positions in a materials test reactor, this poses a problem. The photon source in this case consists of two parts: prompt photons and photons emitted by decaying fission products (*delayed* photons). The prompt photons are commonly taken into account in particle transport codes, but the photons from fission product decay are not.

Here we propose to incorporate the delayed photons by means of a simple engineering correlation, which can easily be implemented in e.g. a Monte Carlo transport code such as MCNP. Our results compare well with data for all experimental positions in the High Flux Reactor (HFR) in Petten, the Netherlands. We also discuss the reduction in heating levels when converting the HFR to LEU.

KEYWORDS: *gamma heating calculations, fission product decay photons, irradiation experiments*

1. Introduction

In materials test reactors many different types of experiments take place. One common factor in all these experiments is that the temperature rises because of radiation heating. In some cases the temperature of irradiated samples goes up to 1000 °C, in most other it is lower. In all cases the temperature should remain within agreed design criteria, and therefore the heat flow needs to be controlled. This means that in the design of an experiment one should take into account a heat removal process capable of removing all the heat generated in the irradiated samples and in the equipment. Clearly one then needs to know, with reasonable but not pin-point accuracy, the amount of heat generated.

The calculation of heating due to neutron irradiation is at the heart of the nuclear industry, and consequently many software packages can do this. However, for experiments in a materials test reactor the heating due to photon irradiation ('gamma heating') is usually dominant. The heating due to photon irradiation can also be calculated by many codes, provided the photon source is known. It is this photon source in a reactor that is the problem. The photon source in this case consists of two parts: photons produced by (n,γ) reactions, fission, or $(n,n'\gamma)$, etc. (sometimes called *prompt* photons), and photons emitted by decaying fission products (*delayed* photons). The prompt photons are commonly taken into account in particle transport codes, but the photons from fission product decay are not.

A source of fission product decay photons can be obtained from codes that perform burn-up calculations: in these codes the amount of unstable isotopes is known at every time step. However, such codes do not transport the photons, which is necessary if you want to know where they deposit their energy. So we are faced with a situation where transport codes have only part of the photon source, and where burn-up codes have the other part but cannot calculate the energy deposition. Ideally one should couple two such codes for the purpose of radiation heating calculations for irradiation experiments. In Ref. [1] such a coupling is described, although in that case the coupling is non-automatic, involving manual

editing stages in Excel. Moreover, the results of the heating calculations were not validated. A fully automatic coupling, however, requires a major effort, which is not necessary for this purpose.

2. New engineering approach

Here we present a more practical, engineering approach, based on the assumption that the reactor is in steady state. For a reactor in steady state there are fits available for the photon production by fission product decay [2]:

$$p(E_\gamma) = Ce^{-1.1E_\gamma/E_0},$$

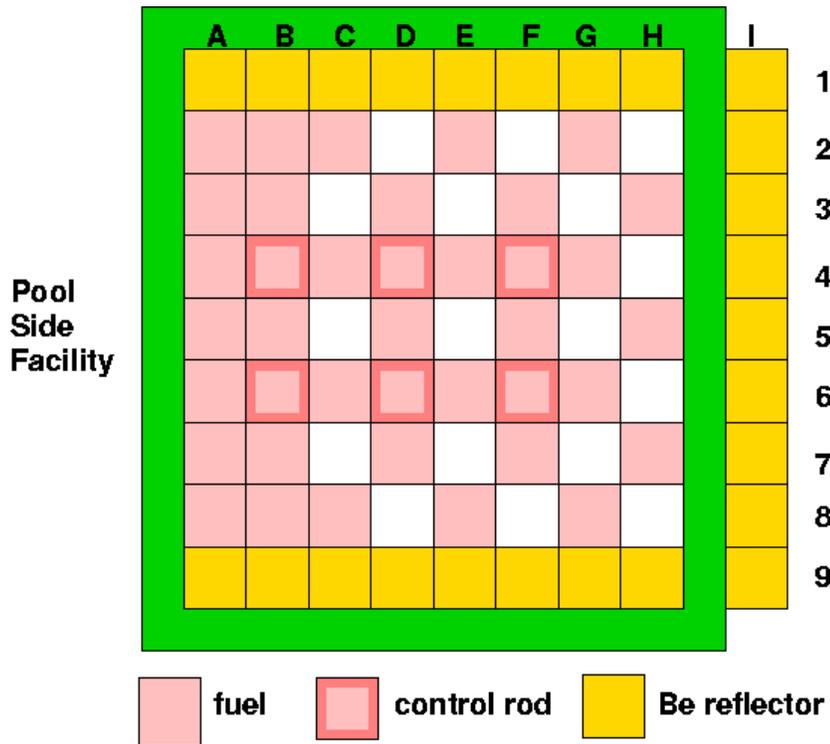
with E_γ being the energy of the photon emitted by a decaying fission product, and $E_0=1$ MeV. The normalization constant C is given in Ref. [2] to be 7.4, in units of ‘photons per fission per MeV’. This means, on average, an energy of 6.72 MeV emitted in the form of photons per fission. The average photon energy, according to this fit, is 1.1 MeV. It should be stressed that the above photon energy distribution is only a rough fit to experimental results, and that when using this in e.g. a Monte Carlo calculation, we implicitly assume that the reactor is in steady state, and that it has been in steady state since $t=-\infty$. However, since about 75% of fission product decay photons is released within 10^3 s after fission, the assumption in practice is that the reactor has been in steady state for more than 15 minutes.

The above photon production equation can easily be added to a Monte Carlo program, for which we choose MCNP [3]. Also in MCNP the fission product decay photons are not taken into account. Moreover, the heating caused by these photons is not included in the heating factors calculated for MCNP (tally f6) by NJOY [4]. To introduce the delayed photons into MCNP, one should generate on average 7.4 photons for each fission event in MCNP, with photon energies according to the above distribution. The distribution can be generated as follows. The corresponding cumulative distribution, normalized to unity, reads $P(E_\gamma)=1-\exp(-1.1E_\gamma/E_0)$. A Monte Carlo realisation of the delayed photon energy according to the distribution $p(E_\gamma)$ is found by solving the equation $P(E_\gamma)=\rho$, where ρ is a (pseudo) random number, uniformly distributed between 0 and 1. The result is $E_\gamma=E_0\ln(1-\rho)/1.1$. The angular distribution is isotropic, which is easy to generate: uniform distributions in terms of $\cos\vartheta$ (polar angle) and φ (azimuthal angle). For efficiency of calculations one can also, instead of generating 7.4 photons per fission, generate one photon with Monte Carlo weight $w=7.4$.

3. Comparison with experiment

We have applied this technique to the calculation of radiation heating in experiment positions in the High Flux Reactor in Petten (the Netherlands). This reactor has a checkerboard pattern of 33 fuel positions, 6 control rod positions, and 17 in-core experiment positions, see Fig. 1. Each position is 7.71×8.1 cm² wide, and the reactor core is 60 cm high. The core is surrounded on three sides by beryllium reflector elements. On the fourth side, on the left in Fig. 1, there is a pool side facility with several irradiation rigs. The reactor is operated at 45 MWth for around 300 days per year. The typical radiation heating, averaged over a full experimental position, ranges from more than 10 W/g in row C, to around 3 W/g in rows G and H.

Figure 1. General lay-out of the High Flux Reactor in Petten, the Netherlands



For each position we calculated (using f6:n,p in kcode mode) average radiation heating in the central 40 cm and the average for the full 60 cm core height. The numbers from MCNP are in MeV/g³/source neutron³. Using a normalization factor based on reactor power (45 MWth), these numbers can be translated to units of W/g. Note that the normalization is based on reactor power vs a similar f6 tally, summed over the whole reactor core. Since the total power is generated mainly in the fuel elements, the calculation of radiation heating in the experimental positions is nevertheless a test whether the photons (and neutrons) produced are transported throughout the reactor core in the correct way.

A drawback of the current comparison is that detailed information on the experiment (that was performed over 20 years ago) was not available. Therefore a simple model was used for the experimental positions, in which there were no materials with strong interactions with neutrons, as would be expected for an experiment of this kind. When comparing the results in units of W/g, the main dependence of photon heating on the material is divided out, so that the resulting comparison tests the number of photons simulated, and their energy, rather than the local interactions. The experimental data have been reported in these units as well, see Ref. [5], enabling easy comparison, see Table 1.

Table 1. Calculated over experimental values (C/E) for the radiation heating in graphite (in units of W/g) in the experiment positions in the HFR. The first entry is for the full core height, the second for the central 40 cm only. The estimated statistical uncertainty is 1%.

	C	D	E	F	G	H
2		1.02 / 1.05		1.02 / 1.01		1.03 / 1.04
3	0.97 / 1.01		1.00 / 1.00		0.99 / 1.01	
4						1.02 / 1.06
5	1.01 / 1.03		1.01 / 1.03		0.99 / 1.02	
6						1.01 / 1.06
7	0.97 / 1.01		0.99 / 1.01		0.96 / 1.01	
8		1.03 / 1.05		1.02 / 1.02		1.03 / 1.04

As can be seen from this Table, the averages over the full core height of 60 cm are accurate, deviating only up to 4% at maximum from the experimental value. The averages over the central 40 cm deviate slightly more, viz. up to 6%.

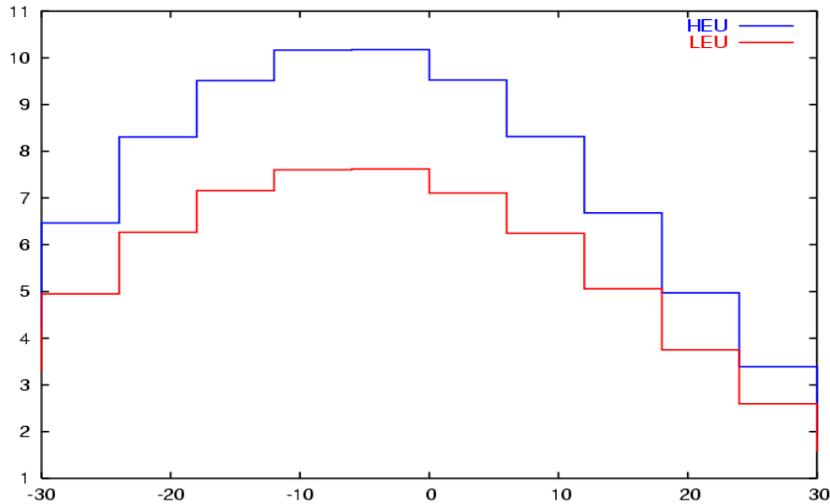
Having checked the validity of the method by comparing with experiments, it is instructive to have a look at some other results. First, it is interesting to ask how much of the radiation heating is caused by the delayed photons, the part that one usually does not get from MCNP. We have estimated that the contribution of the fission product decay photons to the total radiation heating was roughly 40% for all positions. Based on the C/E values in Table 1, we conclude that this contribution is calculated with sufficient accuracy for this application.

Secondly, since the HFR was converted to LEU recently, there was a need to predict as best we could the amount of radiation heating for the LEU converted core. It was in fact this question which prompted us to develop the method presented here. This method was used to calculate the radiation heating in both a HEU core and in an LEU core with the same fuel loading pattern. The result for the ratio of heating in the LEU core divided by that in the HEU core is presented in Table 2.

Table 2. Ratio of radiation heating in a LEU core divided by that in a HEU core. The entries in red are calculated for an experiment containing B-10, i.e. an experiment with sizable neutron absorption. The estimated statistical uncertainty is 1%.

	C	D	E	F	G	H
2		0.802		0.838		0.875
3	0.794		0.833		0.852	
4						
5	0.847		0.885		0.855	
6						0.870
7	0.806		0.902		0.858	
8		0.872		0.853		0.885

Figure 2. The radiation heating (in units of W/g) for position C3 of the HFR, both for a n HEU and an LEU core.



In four positions (C5, D8, E5, E7) the calculations were done for an experiment containing 10B, i.e. an experiment with sizable neutron absorption. For this experiment the total radiation heating decreases by 10 to 15%. For the other positions the same experimental model was used as above in Table 1. There the radiation heating decreases by roughly 15 to 20%. There is a slight tendency for the radiation heating to decrease further in some places (20% in rows C, D) than in others (14% in rows G, H). In reality, the fuel loading pattern was changed during the course of the conversion to LEU, so that Table 2 was not used. But the current method to calculate the radiation heating was used extensively, precisely because the fuel loading pattern was not constant.

4. Conclusions

We conclude that we have introduced and tested a new method to take fission product decay photons into account for stationary reactors, using a simple Monte Carlo implementation of an engineering correlation. This method enables sound predictions of radiation heating in experimental positions in an MTR. The method was used successfully during the conversion of the HFR to low enriched uranium.

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