Effect of Reactor Fuel Enrichment on Gamma Heating of Irradiated Samples

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***Abstract*—Assessment of the gamma heating deposited on samples irradiated in material testing reactors is basic safety issue. The GHRRC (Gamma Heating in Research Reactor Cores) code developed in NCSR "Demokritos" is used here to estimate the relative importance of the mechanisms contributing to the total gamma heating of the irradiated material, for a core fuelled with Low (LEU) and with High Enrichment Uranium (HEU). The Greek Research Reactor core configuration with a 13% burnup has been assumed for the numerical experiments. The gamma heating of a Fe sample irradiated near the core center is examined. The heating components due to fission gammas, capture gammas and gamma dose build-up in the core are compared with respect to the fuel enrichment. Although individual components are found higher either in the LEU or in the HEU core, the total gamma heating is found comparable for the two fuel enrichments.**

***Index Terms*—Core conversion, dose built-up, gamma heating processes, numerical simulation, reactor safety.**

I. INTRODUCTION

IRRADIATION of target materials for research purposes is an everyday activity in material testing reactors. Heating from gamma radiation of irradiated sample materials is an issue of primary importance for the safety and the radiation protection of research reactors. Designing the optimum and safe conditions for sample irradiation experiments, requires calculation of the energy that is expected to be deposited on the target materials by nuclear heating. The nuclear heating in a research reactor core is mostly due to gamma radiation, especially when heavy material samples are irradiated.

Seeing the requirement for conversion of the research reactor cores from HEU (High Enrichment in Uranium) to LEU (Low Enrichment in Uranium), the nuclear heating modification with respect to the fuel enrichment has been subject of investigation, although relevant works are rarely found in the literature. For example, in a work from Petten, an improved Monte Carlo method was used to compute nuclear heating for a HEU and a LEU core with the same fuel-loading pattern, but with different HEU and LEU fuel assembly geometry (i.e. plates/assembly), in the High Flux Reactor (HFR). The nuclear heating in the HEU core was found to be 15 to 20% higher than in the LEU, which was attributed to the absorption of a significant fraction of gamma radiation inside the LEU core due to the presence of a large amount of U238 [1].

The aim of this work is to contribute to the core conversion studies performed within the framework of the RERTR Program [2], by comparing the gamma heating deposited on a sample irradiated in a HEU and a LEU research reactor core; the relative importance of the gamma heating components is also examined in the two core compositions. The analysis is made by GHRRC.

GHRRC (Gamma Heating in Research Reactor Cores) is a home-made, three-dimensional code, developed to estimate the gamma heating of small samples inside a research reactor core. GHRRC was found to give reasonable gamma heating estimations within reasonable error margins [3]. In the present work, GHRRC is applied to estimate the relative importance of the mechanisms contributing to the total gamma heating of an irradiated Fe sample, using the same loading pattern for two different fuel enrichments in U235. In both cases the fuel assemblies have the same geometry, representative of that used in the Greek Research Reactor (GRR-1) core and the same fuel burnup.

The results show that in the HEU core the heating from fission gammas is higher than the one in the LEU core. However, although gamma rays attenuation is higher in the LEU core due to the higher uranium content, the same factor makes the dose build-up more important in the LEU core, leading thus to a net result of higher fission gammas contribution in the LEU than in the HEU core after the build-up process has been taken into account. Concerning the effect of capture gammas (in which build-up in core is included) it is found that the higher U238 content in LEU induces more significant heating by capture gammas from uranium and plutonium (mainly produced in the U238 chain), while the contributions of water, structural materials and fission products are found higher in the HEU core.

II. THE GHRRC CODE

As mentioned above, GHRRC is a three-dimensional numerical code, based on a point-kernel parameterization.

The developed model includes the prompt and delayed photons produced from the U235 fission and the gammas produced by neutron capture ((n, γ) reactions) in the core materials. Empirical correlations are adopted for the dose build-up in the core and the energy absorption build-up in the irradiated sample. The required neutron fluxes are calculated using the neutronics code system NITAWL/XSDRNPM [4], [5] and CITATION [6] in a three-dimensional representation of GRR-1 core, as described in [7]. For the determination of the macroscopic cross sections

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Manuscript received April 03, 2009; revised July 30, 2009. Current version published December 09, 2009.

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Digital Object Identifier 10.1109/TNS.2009.2033912

for the U235 fission and the (n,γ) reactions in the core materials, a homogenization of the core is performed. The attenuation coefficient of the monoenergetic γ-rays is also derived for a homogenized core, as a with-respect-to-density weighted sum of the individual attenuation coefficient values of the various core materials [8]. The same approximation is used for the derivation of the core dose build-up factor based on the values tabulated for each core material.

Thus, the rate of the total gamma energy deposited per unit volume of the sample is computed from:

$$W = \int_{V_c} \int_{E} w(\vec{r}, E) dE d\vec{r}_0 \tag{1}$$

where E is the photon energy, V_c is the core volume and $w(\vec{r}, E)$ is the heat deposited per unit volume of the irradiated sample at position $\vec{r}$, from the monoenergetic gamma rays of energy E released at core position $\vec{r}_0$. In the GHRRC, $w(\vec{r}, E)$ is computed from:

$$\begin{aligned} w(\vec{r}, E)dE = & dE \frac{\mu_{\alpha b}(E)}{\overline{\ell}\mu_{\alpha t}(E)} \left(1 - e^{-\mu_{\alpha t}(E)\overline{\ell}}\right) B_s\left(\mu_{ab}(E)\overline{\ell}, E\right) \\ & \times B_c\left(\mu(E)|\vec{r} - \vec{r}_0|, E\right) E \frac{e^{-\overline{\mu}(E)|\overline{r} - \overline{r}_0|}}{4\pi|\vec{r} - \vec{r}_0|^2} d\vec{r}_0 \\ & \times \sum_n A_n(\vec{r}_0, E)\Phi_n(\vec{r}_0) \end{aligned} \tag{2}$$

where $\mu_{\alpha t}(E)$ and $\mu_{\alpha b}(E)$ (in $[\mathrm{cm}^{-1}]$) are respectively the attenuation and the absorption coefficient of the monoenergetic photons of energy E in the sample material, $\overline{\ell}$ is the mean chord length of the sample defined as $\overline{\ell} = 4V_s/S_s$ with V_s and S_s being respectively the volume and total external surface of the sample [9], B_s is the build-up factor for the energy absorption in the sample material, B_c is the dose build-up factor in the homogenized core, $\overline{\mu}(E)$ is the attenuation coefficient of the photons of energy E in the homogenized core, $\Phi_n(\vec{r}_0)$ is the neutron flux at core position $\vec{r}_0$ for neutron energy group n and A_n is given from the relationship:

$$A_n(\vec{r}_0, E) = \sum_j \Sigma_{j,n}(\vec{r}_0)Y_{j,n}(E) + \Sigma_{f,n}(\vec{r}_0)X_n(E) \tag{3}$$

where, $\Sigma_{jn}(\vec{r}_0)$ (in cm^{-1}) is the macroscopic cross section of (n,γ) reaction for nuclide 'j', with neutrons of the energy group 'n' at core position $\vec{r}_0$, $Y_{jn}(E)$ (in J^{-1}) is the spectrum of gamma rays of energy E due to (n,γ) reactions in nuclide 'j', with neutrons of the energy group 'n', $\Sigma_{f,n}(\vec{r}_0)$ (in cm^{-1}) is the fission macroscopic cross section of neutron energy group 'n' at the core position $\vec{r}_0$ and $X_n(E)dE$ is the probability that a photon of energy between E and $E + dE$ results from fission-produced neutron at the energy group 'n'. Exponential fits are used in GHRRC for $X_n(E)dE$ [10], [11] while for $Y_{j,n}(E)$ the discrete values of PGAA-IAEA and NNDC databases have been included [12], [13].

It should be noted that in the present application only the gamma rays produced from reactions (fission and capture) with thermal neutrons have been considered, due to lack of gamma rays yield data for epithermal neutrons reactions.

In GHRRC, the energy integration is performed using the trapezoidal method, while a 21-Point, 5th-degree of accuracy formula for triple integrals is used for the volume integration [14].

GHRRC is suitable for the present analysis, since it is capable of calculating the gamma heating components separately, with respect to the different reaction types, i.e. fission, core build-up and capture by individual nuclides. The code is written in ANSI Fortran 77, it is open source and can be very easily handled, even by poorly experienced users.

III. APPLICATION TO THE GRR-1 CORE

GRR-1 is a slab-geometry, pool type, light water moderated and cooled reactor, using beryllium reflectors and fueled by MTR-type fuel elements, normally operating at 5 MW. The active core dimensions in x, y (horizontal) and z (vertical) directions are 45.66 cm, 47.74 cm and 62.55 cm respectively. The horizontal core configuration is shown in Fig. 1, in x (letters) and y (numbers) coordinates. The core is composed of 28 standard and 6 special fuel assemblies, including 18 and 10 fuel plates respectively. Five of the special fuel assemblies host a shim/safety control rod. The grid position D4 hosts a control fuel assembly without control rod and is used for materials' irradiation in high fluxes. Grid positions A7 and F7 are also used as irradiation channels but in lower fluxes. Details about GRR-1 features are given in [7]. Two critical core configurations are used in this work, with conceptual fuel composition. In the first one only LEU fuel is considered (19.75% U235) containing 62.48g U per fuel plate, while in the second only HEU fuel is considered (93% U235) with 10.8g U per fuel plate. In both cases the U235 burn-up was considered 13%.

The gamma heating of a Fe cylindrical sample of 5 cm height and 0.7 cm diameter, placed in the middle of the grid channel D4, was calculated using GHRRC. The heating components considered in the computations include (i) prompt and delayed fission gammas, (ii) capture gammas originated from heavy nuclides, fission products, structural materials and water and (iii) the gamma dose build-up in the core and the energy absorption build-up in the sample. For the capture gammas from fuel plate, indicative isotopes were examined (i.e. isotopes of U, Pu and Sm), based on the relative importance of their macroscopic absorption cross section and the data availability for their photon capture spectra.

It should be noted that the γ-rays produced from thermal capture by several nuclides that are present in the irradiated fuel plates were not taken into account, since their (n,γ) spectra were not available. Thus nuclides with significant (n,γ) cross section in the thermal range, such as Xe135, Sm151, Pu241, Pm isotopes and others, were omitted. This is expected to induce in both examined cases underestimations of the total gamma heating, which are discussed in the following section. The same holds for the capture gammas from the beryllium blocks and the surrounding pool water which are not considered, since their homogenization with the active core would introduce more significant error than their omission.

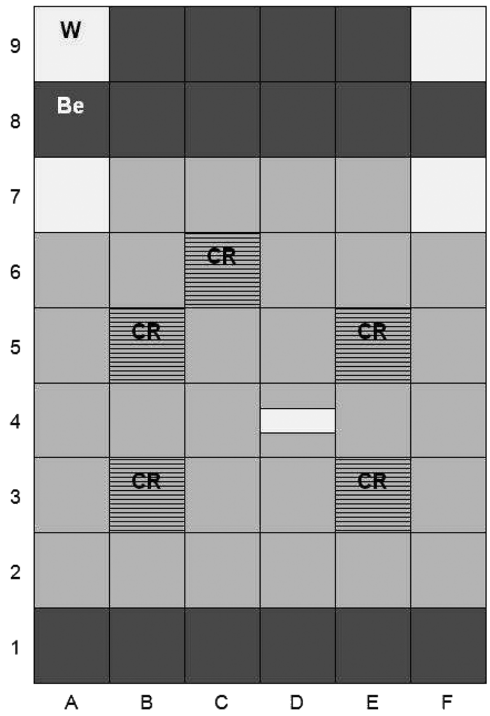

Fig. 1. Horizontal cross section of the GRR-1 Core. The notation is: **CR** for control fuel assemblies with control rods inserted, **W** for water and **Be** for beryllium reflectors.

The computational domain includes the core shown in Fig. 1, with 20 cm of surrounding pool-water in all six sides. The three-dimensional group-averaged neutron flux in the GRR-1 core as well as the densities of the nuclides contained in the irradiated fuel inventory were calculated using the neutronics code system NITAWL/XSDRNPM and CITATION with the NDF5 238-group SCALE library. Thus, separate homogenized zones as described in [7], were defined for the core analysis by CITATION, while resonance shielding and cell calculations were performed by NITAWL/XSDRNPM, collapsing the energy spectrum in five neutron energy groups, the thermal threshold being at 0.5 eV. The macroscopic cross sections of the U235 fission and the (n,γ) reactions in the core materials, Σ_f and Σ_j respectively, were determined assuming a homogenized core, through the relationship:

$$\langle \Sigma_c \rangle = \frac{\sum_{i=1}^{nz} \sigma_{j,i} N_{j,i} V_i}{V_c} \tag{4}$$

where $\langle \Sigma_c \rangle$ stands for Σ_f or Σ_j, nz is the number of homogenized zones that include the nuclide j (e.g. for a nuclide of the fuel meat, nz is equivalent to the number of fuel assemblies), $\sigma_{j,i}$ is the equivalent microscopic cross section (fission or capture, provided by XSDRNPM) of the nuclide j in the zone i, $N_{j,i}$ is the number density of the nuclide j in the zone i, V_i is the volume of zone i and V_c is the volume of the active core, i.e. without beryllium blocks and surrounding pool water.

TABLE I
GAMMA HEATING POWER DENSITY DEPOSITED IN A Fe SAMPLE FROM SEVERAL MECHANISMS, FOR TWO DIFFERENT FUEL ENRICHMENTS IN U235

Gamma heating component	**W_c (W/cm^3) LEU**	**W_c (W/cm^3) HEU**
Non Built-up Fission	8.89	10.85
Built-up Fission	15.56	15.08
Capture U	0.035	0.008
Capture Al	0.732	0.825
Capture Pu	0.454	0.00012
Capture H	0.542	0.595
Capture Sm	0.0308	0.0324
Capture Si	0.0152	0.000
Total γ-Heating (sum of built-up fission and capture components)	17.369	16.540

IV. RESULTS AND DISCUSSION

The results obtained are shown in Table I. As can be seen, higher heating from uncollided fission gammas is found in the HEU than in the LEU core, which can be attributed to the higher thermal neutron flux as well as to the lower gamma rays attenuation (due to the lower U238 content) in the HEU core. However, the higher uranium content in the LEU core also induces a more important dose build-up factor. Thus, at least for HEU and LEU assemblies of identical geometry, the net result of the higher uranium content in the LEU core is the higher power density deposited on the sample from fission gammas, compared to that in the HEU core. Also, in LEU fuel the higher quantity of uranium makes heating by capture gammas from U more significant than in HEU, while the higher U238 content increases the gamma heating from neutron capture in the produced Pu isotopes. The Si contribution (existing only in LEU) is found of small importance. The contribution of in-core water, structural materials and fission products is found higher in the HEU core. This is mainly attributed to the dominance (among the mechanisms that affect the final results) of the higher thermal neutron fluxes that prevail in the HEU core. In particular, aluminium contribution is enhanced in the HEU core due also to the higher Al content in the HEU meat.

It should be noted that the results in Table I are expected to underestimate the gamma heating power density actually deposited on the sample, due to (a) the omission from calculations of heating mechanisms such as activation of nuclides, epithermal capture and thermal capture in several core compartments and fuel plate nuclides and (b) the core homogenization at least for the core materials that are not really distributed in the core. On the other hand, the omission of (n,γ) reactions in several nuclides of the irradiated fuel may have induced higher underestimations either in the LEU or the HEU case, depending on the omitted nuclide. For example, the omission of Pu241 is expected to cause more significant underestimation to the LEU result, while the omission of (n, γ) in fission products, such as Xe, Pm and some Sm isotopes, is expected to cause higher underestimation in HEU. However, at least for the studied core features, the results can be considered comparable for the two fuel enrichments.

An additional conclusion that is drawn comparing the results found for the GRR-1 core configuration with those found for HFR [1], is that the relationship between a HEU and a LEU core with respect to the gamma heating deposited on a irradiated sample may depend on the core characteristics, including the fuel assemblies' geometry and U density. Thus, in the GRR-1 case both HEU and LEU fuel assemblies have the same dimensions and number of fuel plates, whereas in the HFR case, the HEU standard fuel assemblies contain three fuel plates, and the special fuel assemblies contain two fuel plates more than the LEU ones. Also, the uranium density in the GRR-1 LEU fuel is 5.79 times higher than in the HEU, whereas the corresponding ratio for HFR is 4.4 for the standard and 5 for the special fuel elements.

V. CONCLUSIONS

In this work, GHRRC was applied to two different core configurations (LEU and HEU) of the Greek Research Reactor (GRR-1). The gamma heating power density deposited in a Fe sample located in the middle of a central irradiation channel of the core was computed. Comparison of the gamma heating between the two configurations showed that the higher thermal neutron flux in the HEU core causes higher heating from fission gammas than in the LEU core. However, the higher uranium content in LEU makes the dose build-up more important in the LEU core. Also, in the LEU fuel, the higher quantity of uranium induces more significant heating by capture gammas in U, while the higher U238 content causes higher heating from capture gammas in produced Pu isotopes, compared to the HEU core. The Si contribution (existing only in LEU) is found of small importance while the contributions of water, structural materials and fission products are found higher in the HEU core, due also to higher neutron fluxes. The omission of surrounding materials, such as the reactor pool water and the beryllium blocks, may have caused underestimation of the total gamma heating, which is expected higher in the case of LEU core, since the build-up of the gamma rays that travel towards the sample is expected more significant in LEU. On the other hand, the omission of (n, γ) reactions in several nuclides of the irradiated fuel, mainly due to the lack of available data, have induced underestimations which might be higher either in the LEU or in the HEU core, depending on the omitted nuclide. However, the results are considered comparable for the two fuel enrichments, a finding that can be very useful in cases of core conversion studies, since the transition from a HEU to a LEU core does not seem to yield significant safety issues rising from the gamma heating, if the core and the fuel assembly geometries are conserved and typical fuel compositions are used.

Taking into consideration similar studies made for other reactors, it seems that the relative importance of the gamma heating deposited on a sample irradiated in a HEU and a LEU core depends on the fuel assemblies' geometry and the U density. The results obtained in the present study are related to the GRR-1 fuel (geometry, enrichment, U density), which is widely used in research reactors of the same type, and thus the obtained results can be of wider interest.

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