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Photon transport effect on intra-subassembly thermal power distribution in fast reactor

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Abstract

In order to accurately predict intra-subassembly thermal power distribution in a fast reactor, neutron and photon transport calculations are carried out with a multi-purpose reactor physics calculation code system CBZ. All the fission fragment nuclide are treated explicitly during fuel depletion, and irradiation time-dependent energy spectra of delayed fission γ -rays emitted from all the fission fragment nuclides are precisely simulated. Time-dependent delayed β -ray emission and transmutations of fission fragment nuclide by neutron-nuclide reactions are also taken into account. A fuel subassembly model of Japanese prototype fast reactor Monju is used for numerical calculations, and their two-dimensional geometric feature is precisely modeled by a ray-tracing-based collision probability method implemented in CBZ. When the photon transport is considered, total thermal powers in fissile material regions are reduced by about 1.5% except at the beginning of fuel depletion.

Key words: thermal power distribution, fast reactors, photon transport

1. Introduction

Accurate prediction of thermal power spatial distribution in a nuclear fission reactor core is essential for reliable and efficient reactor core designs. In addition to macroscopic spatial power distribution over a whole core required to allocate coolant flow in the core, a microscopic power distribution, *i.e.*, intra-subassembly thermal power distribution, is also important to determine nuclear fuel depletion, neutron irradiation of structure materials and temperature evaluations. In fast reactor core designs, a maximum fuel temperature is one of the most important design parameters and it sometimes restricts a feasible design range.

As well known, nuclear fission reactions release a large amount of energy with some different forms such as kinetic energy of fission fragments, prompt γ - and β -rays, delayed γ - and β -rays emitted from unstable fission fragments. In addition to fission reactions, γ -rays generated by several neutron-nuclide reactions such as (n,γ) and (n,n') reactions also contribute to thermal power generations. Energy given to nuclides by

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18 neutron scattering reactions is also not negligible. The simplest way to calculate thermal power distribution
19 coming from these different forms is to determine an effective fission Q-value, Q_f . A thermal power can
20 be obtained by multiplying total number of occurring fission reactions by Q_f . Historically this simple
21 calculation method has been used with some improvement in fast reactor design studies. Its detail is well
22 reviewed in a reference (Hazama, 2013).

23 In this simple treatment, all the heats generated by a fission reaction are deposited to a medium in which
24 the fission reaction occurs. Actually γ -rays generated by neutron-nuclide reactions and radioactive decay
25 of unstable fission fragments transport in a core and deposit their energy to a medium which is different
26 from a originating medium. This is referred to as a γ -ray (or photon) transport effect on thermal power
27 distribution in the present paper.

28 Procedure of photon transport effect evaluation is quite simple; one has to calculate γ -ray sources from
29 neutron-nuclide reaction rate distributions, and perform a fixed source photon transport calculation with
30 a particle transport code. Thermal power distribution induced by photons can be obtained from photon
31 flux distribution and the KERMA (Kinetic Energy Release in MAterials) factors of mediums consisting of
32 a reactor core. A reference (Hazama, 2013) reports that the photon transport effect increases heats in fast
33 reactor blanket and shielding regions about 10%. The importance of the photon transport effect has been
34 well recognized and this effect has been taken into consideration somehow in fast reactor core design studies.

35 Although the photon transport effect can be easily evaluated as above mentioned, there is a difficulty
36 in calculating γ -ray sources originating from radioactive decay of fission fragments: so called the delayed
37 fission γ -rays. Since a strength and energy spectrum of the delayed γ -rays depend on an irradiation profile,
38 they cannot be uniquely determined. In actual calculations of the photon transport effect, however, fission
39 fragment compositions are calculated by assuming an appropriate irradiation condition and a unique delayed
40 γ -ray spectrum per a fission reaction is determined for each fissile nuclide. Then these γ -ray spectra are used
41 commonly during fuel depletion to calculate γ -ray sources. Some have assumed an infinite irradiation since
42 fission fragment compositions can be analytically calculated (Hazama, 2013; Maeda, 2013). This infinite
43 irradiation assumption, however, considers only nuclide transmutations by radioactive decay and cannot
44 treat transmutations by neutron-nuclide reactions.

45 In the present study, we evaluate the photon transport effect on intra-subassembly thermal power distri-
46 bution in a fast reactor. A notable point of this study is to rigorously simulate irradiation time-dependent
47 delayed γ -ray sources by simulating explicitly nuclide transmutations of all the fission fragment nuclides by
48 both the radioactive decay and the neutron-nuclide reactions.

2. Numerical calculation procedure

All the numerical calculations are performed with a multi-purpose reactor physics calculation code system CBZ, which is being developed at Hokkaido university. The CBZ code system has been well validated through a post-irradiation examination analysis (Kawamoto, 2012).

2.1. Multi-group neutron and photon libraries

Multi-group neutron and photon libraries are generated from JENDL-4.0 (Shibata, 2011) by the NJOY-99 code (MacFarlane, 2010). The covered energy ranges and the numbers of energy groups are from 10^{-5} eV to 10 MeV and 70 for the neutron library, and from 1 keV to 50 MeV and 42 for the photon library. A lethargy width of all the energy groups except for the final one (from 10^{-5} eV to 0.322 eV) is 0.25 in the neutron library. The energy group structure of the neutron library has been utilized for fast reactor neutronics calculations in Japan. The energy group structure of the photon library is the same as the VITAMIN-J 42-group structure. Options for the weight function choice in NJOY-99 are set to $iwt=7$ in the neutron library generation and $iwt=3$ in the photon library generation. Self-shielding factor tables for the neutron library are generated using the narrow resonance approximation for neutron flux representation.

2.2. Treatment of fission fragment nuclide transmutation

Decay data of fission fragment nuclide such as decay constants, decay modes and their branching ratios, decay energy and delayed γ -ray spectra are taken from the JENDL FP Decay Data File 2011 (JENDL/FPD-2011) (Katakura, 2011). The delayed γ -ray spectrum is energy-integrated to the 42-group structure of the photon library. Fission yield data are taken from the JENDL FP Fission Yields Data File 2011 (JENDL/FPY-2011) (Katakura, 2011). We treat all the fission fragment nuclide explicitly in nuclide transmutation calculations. Neutron-nuclide reactions are also considered in the transmutation calculations for 406 nuclides to which the evaluation data are provided in JENDL-4.0. Although neutron-nuclide reaction data are not evaluated for extremely short-lived nuclides in JENDL-4.0, the neutron-nuclide reactions of such nuclides seems negligible in the present heating calculations. The neutron-nuclide reaction rates are obtained in multi-group neutron transport calculations described in the following subsection, and then nuclide transmutation calculations are performed with the matrix exponential method with the Chebyshev rational approximation (Pusa, 2010).

2.3. Neutron and photon transport calculations

We perform neutron and photon transport calculations for a two-dimensional fast reactor fuel subassembly model. The resonance self-shielding effect is evaluated by the method proposed by Tone (Tone, 1975). Whereas the numerical accuracy of this method is inferior to more advanced methods such as the sub-group

80 method, it has been shown in the previous study that Tone's method can treat spatially-dependent intra-
81 subassembly resonance self-shielding effect of a fast reactor subassembly well (Chiba, 2003). The resonance
82 self-shielding effect is also taken into consideration in γ -ray production cross sections; γ -ray production
83 cross sections are calculated by multiplying the self-shielded neutron-nuclide reaction cross sections by γ -ray
84 yield. The resonance self-shielding calculation is carried out only at the initial depletion step, and the same
85 energy-averaged microscopic cross sections are used in subsequent depletion steps.

86 After obtaining medium-wise multi-group neutron and photon cross sections, neutron transport calcu-
87 lations are performed by a collision probability-based module of CBZ with an eigenvalue calculation mode.
88 Collision probabilities are calculated by the ray-tracing method with the periodic boundary conditions. The
89 maximum distance between two parallel neighboring rays is 0.01 cm and the azimuthal angle is divided to 48.
90 γ -ray sources promptly emitted from neutron-nuclide reactions are determined from the calculated neutron
91 flux and reaction rate distributions, and then the delayed γ sources emitted from radioactive decay of fission
92 fragments are added to them. Finally a photon transport calculation is performed with the same collision
93 probability-based module of CBZ. In both the neutron and photon transport calculations, the scattering
94 anisotropy is considered by the transport approximation.

95 *2.4. Power distribution calculations*

96 We calculate the following component-wise power distributions.

- 97 • The kinetic energy of fission fragments and prompt β -ray energy. The sum of these energy per a fission
98 reaction, E_{FR} , is given in evaluated data files. We use the evaluated data given in JENDL-4.0 for each
99 fissionable nuclide. This power component can be calculated by multiplying total number of fission
100 reactions by E_{FR} for all fissionable nuclides.
- 101 • The delayed β -ray energy. This component is calculated from β -ray energy per a radioactive decay,
102 decay constants and number densities of all fission fragment nuclides included in fuel regions.
- 103 • The γ -ray energy. This component includes the prompt and delayed fission γ -ray and other neutron-
104 nuclide reaction-induced γ -ray. This component is calculated by multiplying photon flux by the
105 KERMA factor.
- 106 • Energy deposited to nuclides by elastic scattering reactions with neutrons. This component is calcu-
107 lated from neutron elastic scattering reaction rates.

108 In order to evaluate the photon transport effect on thermal power distribution, we also perform a thermal
109 power distribution calculation without considering photon transport. In such calculations, all the γ -ray
110 sources energy is deposited to a medium from which the γ -ray originates.

111 Note that only emitted γ -ray energy is taken into consideration in inelastic scattering reactions; energy
112 deposited to nuclides by inelastic scattering reactions with neutrons is ignored in the present study.

113 3. Numerical results

114 3.1. Validation of nuclide transmutation calculation capability of CBZ

115 To show a validity of the CBZ capability for nuclide transmutation calculations with over 1,000 fission
116 fragment nuclides, we calculate β - and γ -ray components of plutonium-239 decay heat after burst fission
117 by fast neutrons and compare them with experimental values obtained at Yayoi (Akiyama, 1982). The
118 results are shown in **Figs. 1** and **2**. The experimental values of both the β - and γ -ray components are well
119 reproduced by CBZ and these results are consistent with previous results obtained by Katakura (Katakura,
120 2011). Thus we can confirm the validity of the nuclide transmutation calculation capability of CBZ.

121 3.2. Photon transport effect on power distribution

122 3.2.1. Calculation condition

123 We evaluate the photon transport effect on thermal power distribution for a fuel subassembly model
124 of Japanese prototype fast reactor Monju. The Monju fuel subassembly is a typical sodium-cooled fast
125 reactor's one; fuel pins are located in a hexagonal array and contained by a stainless-steel wrapper tube.
126 **Figure 3** shows a geometric specification of the Monju fuel subassembly. Some numerical data of the
127 geometric specification are given below.

- 128 • subassembly pitch: 11.56 (cm)
- 129 • duct (wrapper tube) thickness: 0.3 (cm)
- 130 • number of fuel pins in a subassembly: 169
- 131 • outer radius of cladding: 0.325 (cm)
- 132 • outer radius of fuel pellet: 0.278 (cm)

133 A gap between fuel pellet and cladding is mixed to the fuel pellet region for simplification in the present
134 calculations. The detail specification can be found in a reference (Takashita, 2000).

135 The reactor core of Monju consists of two different fuel zones, *i.e.*, inner and outer cores, and the
136 plutonium enrichment of the fuel is different between inner and outer core zones. In the present calculations,
137 we consider these two different fuel compositions. The number densities of fuel pellet, cladding and coolant
138 regions are summarized in **Table 1**. Temperatures of fuel pellet, cladding and coolant regions are set to
139 1,370, 750 and 750 kelvin, respectively.

140 In fuel depletion calculations, we assume that the neutron flux level is constant during fuel depletion.
141 Averaged neutron flux levels in fuel regions are set to 3.7×10^{15} and 3.1×10^{15} [$/\text{cm}^2 \cdot \text{s}$] for inner and outer core
142 subassemblies, respectively. Time steps at which intra-subassembly thermal power distribution is calculated
143 are 0.01, 0.1, 1.0, 10, 100, 1,000 and 10,000 hours.

144 *3.2.2. Irradiation time-dependent delayed γ -ray energy spectra*

145 **Figure 4** shows irradiation time-dependent delayed γ -ray energy spectra in the inner core subassembly.
146 Whereas a little time dependence is observed in the shapes of these energy spectra, effect of this time-
147 dependence of γ -ray spectra seems negligible in actual γ -ray transport calculations.

148 *3.2.3. Irradiation time-dependent thermal power*

149 **Figure 5** shows irradiation time-dependent total thermal power and its component of kinetic energy of
150 fission fragments and prompt β -ray energy. **Figure 6** shows other thermal power components of the inner
151 core subassembly: γ -ray energy, elastic scattering reaction energy and delayed β -ray energy. A figure for
152 the outer core subassembly is omitted here since the almost same trend is observed as that for the inner
153 core subassembly. The thermal power is defined as a whole fuel subassembly power per a unit axial length.
154 Total thermal power gradually increases at the beginning of fuel depletion, and it begins to decrease after
155 100 hours of irradiation. This trend is found commonly in both the inner and outer core subassemblies. The
156 gradual increase in the thermal power at the beginning is due to gradual increases in the delayed γ - and
157 β -ray components. The thermal power decrease after 100 hours of irradiation comes from a fissile nuclide
158 depletion since the constant flux is assumed during the fuel depletion. The γ -ray and the delayed β -ray
159 components also decrease at the end of the fuel depletion since the total number of fission reactions decreases
160 around the time. The elastic scattering reaction component is almost constant during the fuel depletion.

161 In order to see the effect of neutron-nuclide reactions of fission fragment nuclides on thermal power,
162 a different calculation without considering these reactions is carried out. A change in thermal power is
163 negligible and we can conclude that the neutron nuclide reactions of fission fragments are not important to
164 evaluate the delayed γ - and β -ray contributions to the thermal power in the fast reactor Monju.

165 *3.2.4. Photon transport effect on thermal power distribution*

166 **Figure 7** shows the total thermal powers in fissile material regions (fuel pellet regions) which are
167 calculated with/without considering the photon transport and **Table 2** summarizes region-wise thermal
168 powers at the irradiation step of 100 hours. Since consideration of the photon transport makes some of
169 the photon energy deposited to non-fuel mediums, especially to cladding and wrapper tube regions, the
170 total thermal powers in fuel regions becomes smaller. **Figure 8** shows the photon transport effect on total
171 thermal power in the fuel pellet regions, which are defined as a ratio between two total thermal powers in
172 the fuel pellet regions calculated with/without considering the photon transport. Since the delayed γ - and
173 β -ray components are quite small, the photon transport effect takes the smallest value at the beginning of
174 the fuel depletion. Even in this extreme case the power reduction in the fuel pellet regions by considering
175 the photon transport is greater than 1.0%. At the time steps after the irradiation time of 10 hours, the
176 transport effects are around 0.985. This value can be used for Monju core design studies since a thermal full

177 power is rarely attained at the beginning of actual fast reactor operations. **Figure 9** shows fuel pin-wise
178 photon transport effect on thermal powers of fuel region and of fuel and cladding regions in the inner core
179 subassembly. The photon transport effect is larger in the subassembly peripheral region since the some of
180 the photon energy are deposited to the wrapper tube region and the sodium region outside the wrapper
181 tube.

182 **4. Concluding Remarks**

183 In order to accurately predict intra-subassembly thermal power distribution in a fast reactor, neutron
184 and photon transport calculations have been carried out with a multi-purpose reactor physics calculation
185 code system CBZ. All the fission fragment nuclide have been treated explicitly during fuel depletion, and
186 irradiation time-dependent energy spectra of delayed fission γ -rays emitted from all the fission fragment
187 nuclide have been precisely simulated. Time-dependent delayed β -ray emission and transmutations of fission
188 fragment nuclide by neutron-nuclide reactions have been also taken into account. A fuel subassembly
189 model of Japanese prototype fast reactor Monju has been used for numerical calculations, and their two-
190 dimensional geometric feature has been precisely modeled by a ray-tracing-based collision probability method
191 implemented in CBZ. When the photon transport is considered, total thermal powers in fissile material
192 regions are reduced by about 1.5% except at the beginning of fuel depletion. Reduction of the thermal
193 power is larger in fuel pins around a peripheral region of fuel subassemblies since some of photon energy are
194 deposited to a wrapper tube and its outer regions.

195 It has been also shown that neutron-nuclide reactions of fission fragment nuclides are negligible in eval-
196 uation of the photon transport effect on thermal power. Since the neutron-nuclide reactions are much more
197 important in thermal neutron reactors, the present numerical procedure will be applied to thermal power
198 calculations for thermal reactors in future.

199 **Acknowledgements**

200 The authors are grateful to Dr. Jun-ichi Katakura of Nagaoka University of Technology for his advices
201 throughout this study.

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Table 1: Nuclide number densities of Monju fuel subassembly

Region	Nuclide	Number density (/barn/cm)	
		Inner core	Outer core
Fuel pellet	Pu-239	2.54335E-03*	3.42379E-03
	Pu-240	1.04803E-03	1.41083E-03
	Pu-241	6.08807E-04	8.19558E-04
	Pu-242	1.73225E-04	2.33190E-04
	U-235	3.09698E-05	2.80175E-05
	U-238	1.52587E-02	1.38041E-02
	O-16	3.84330E-02	3.88474E-02
Cladding	Cr-Nat.	1.70972E-02	
	Fe-Nat.	6.13318E-02	
	Ni-Nat.	1.20286E-02	
	Mn-55	1.42779E-03	
	Mo-Nat.	1.36265E-03	
Coolant	Na-23	2.25394E-02	

* Read as 2.54335×10^{-3} .

Table 2: Region-wise thermal power at t=100 hours (unit: kW/cm)

Region	Inner core		Outer core	
	w Tr.*	w/o Tr.**	w Tr.	w/o Tr.
Fuel pellet	36.664	37.226	38.807	39.389
Cladding	0.504	0.230	0.483	0.196
Wrapper tube	0.348	0.103	0.331	0.139
Sodium inside wrapper tube	0.158	0.083	0.149	0.073
Sodium outside wrapper tube	0.037	0.020	0.035	0.018

* With photon transport, ** Without photon transport

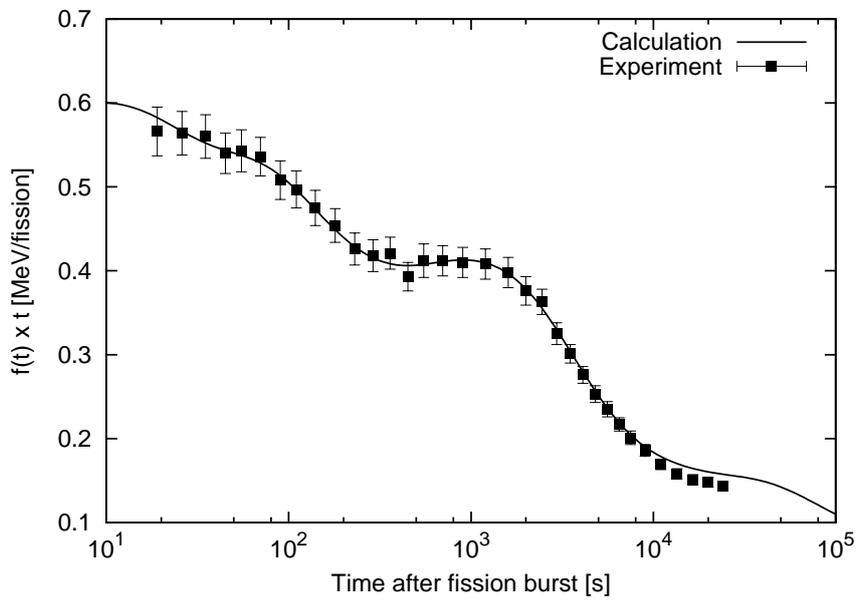


Figure 1: β -ray component of plutonium-239 decay heat after burst fission by fast neutrons

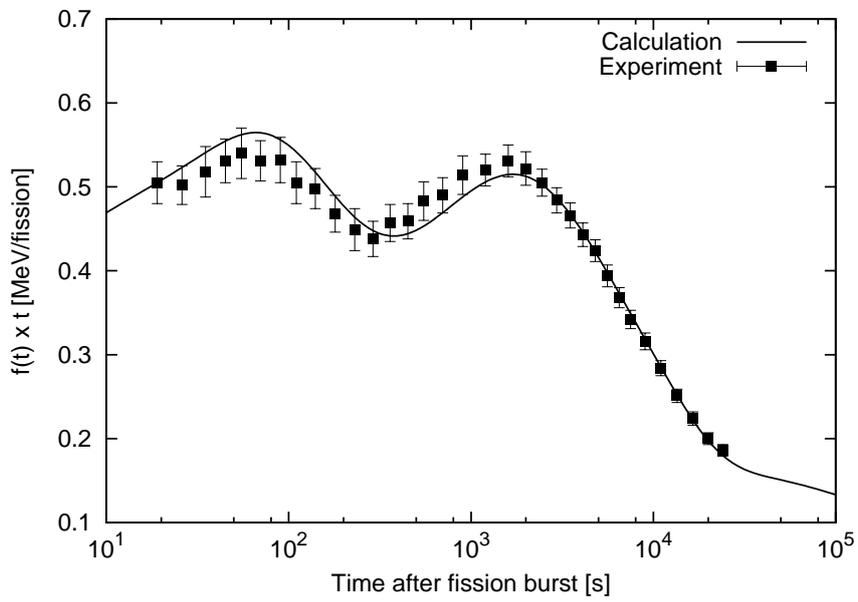


Figure 2: γ -ray component of plutonium-239 decay heat after burst fission by fast neutrons

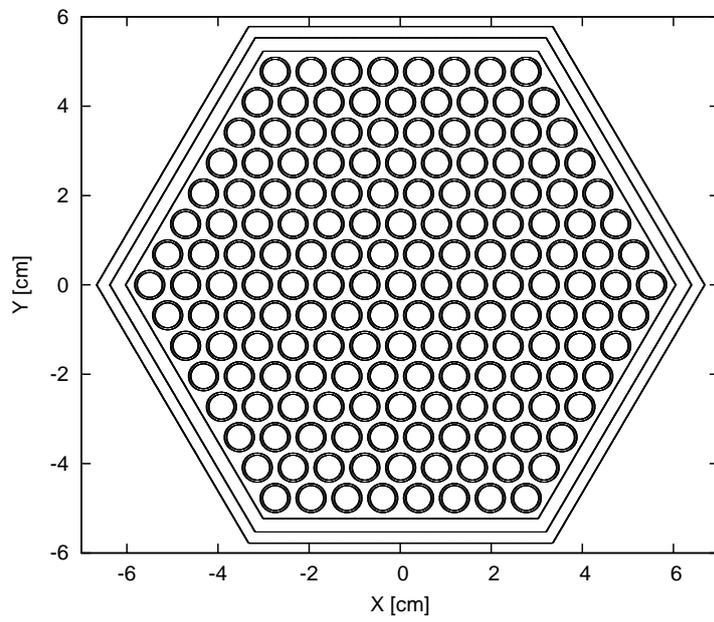


Figure 3: Specification of fuel subassembly of Japanese prototype fast reactor Monju

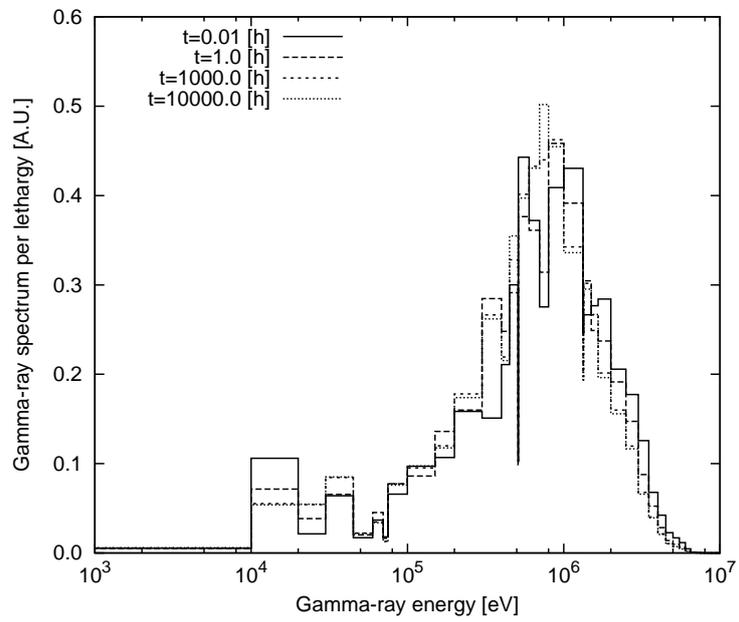


Figure 4: Irradiation time-dependent delayed γ -ray energy spectra

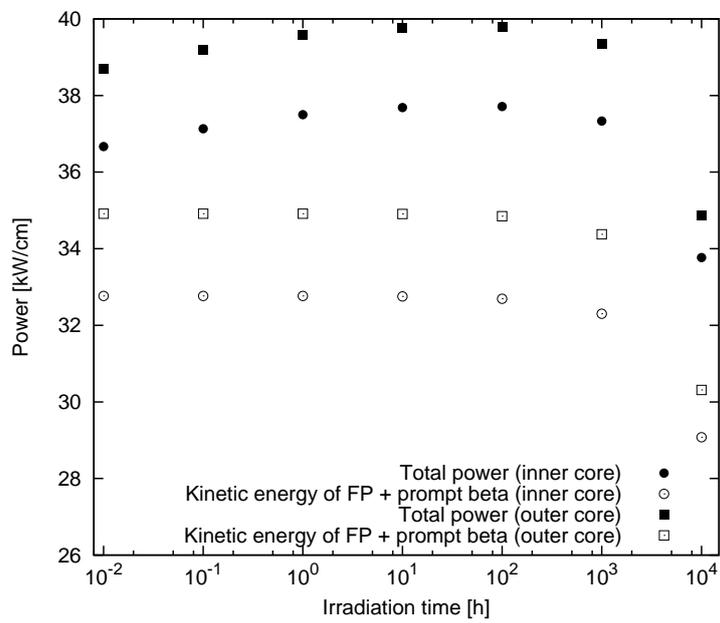


Figure 5: Irradiation time-dependent total thermal power and its component of kinetic energy of fission fragments and prompt β -ray energy

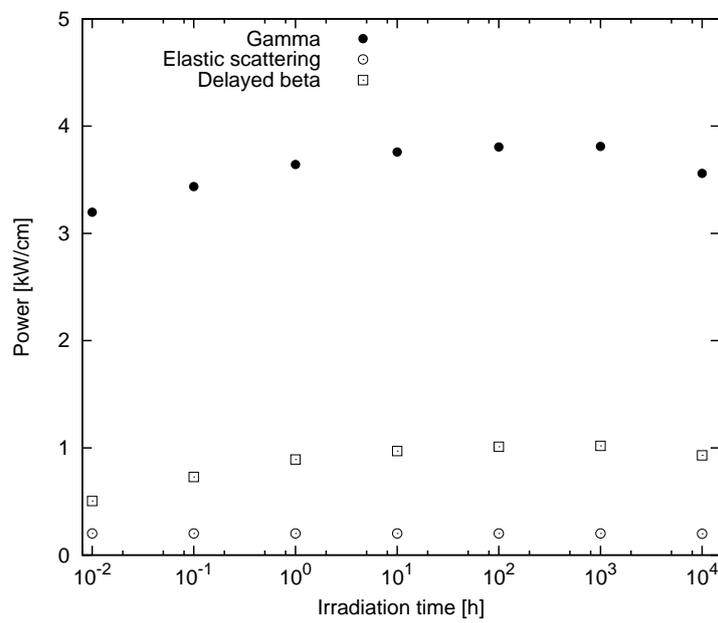


Figure 6: Irradiation time-dependent thermal power components: γ -ray energy, elastic scattering reaction energy and delayed β -ray energy

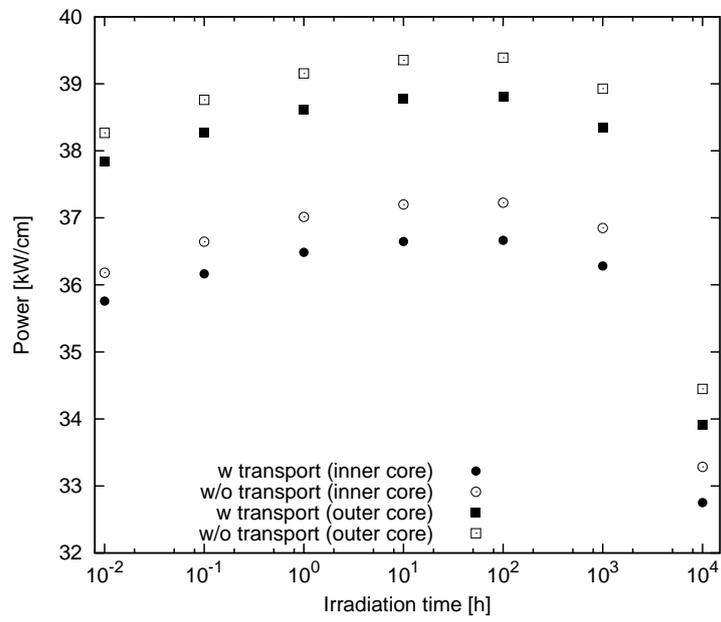


Figure 7: Thermal power in fuel regions with and without consideration of photon transport

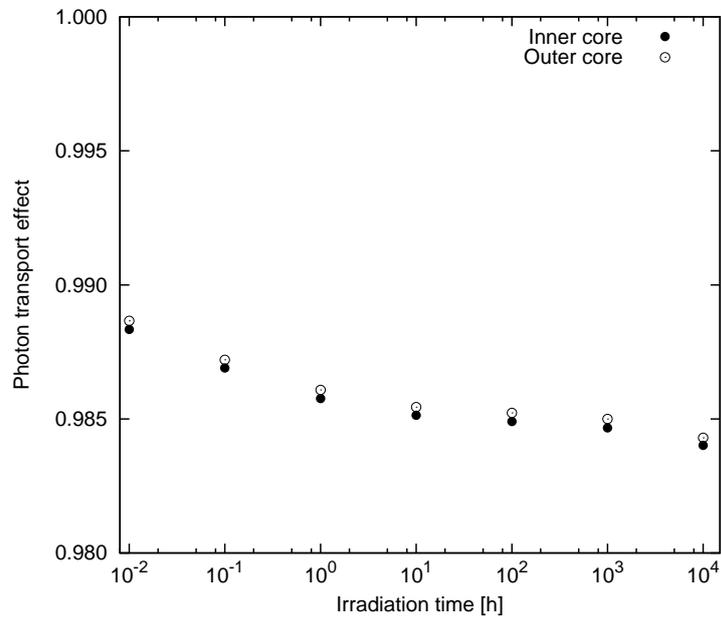


Figure 8: Photon transport effect on thermal power in fuel pellet regions

225 **List of Figure Captions**

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