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VALIDATIONS OF GAMMA MEASUREMENTS IN RESEARCH REACTORS WITH MCNP FULL-REACTOR MODELS

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Abstract

MCNP full-reactor models of the SLOWPOKE-2 and ZED-2 research reactors have been used for calculating gamma spectra and dose rates at locations where measurements were made.

In addition to neutrons, MCNP criticality calculations are capable of tracking reactor prompt photons in space and energy, which can be tallied at locations of interest. Delayed photons from conceivable sources can be approximately included in the calculations, contributing to as much as 1/3 of the local photon intensity or committed dose rate in this study.

Discrepancies between the MCNP calculated and measured results are analyzed for causes.

1. Introduction

Being always present along with neutrons in nuclear reactors, gammas are mostly considered to be parasites as they heat up irradiation samples, structures or instrumentation devices where heating is harmful. In particular, gammas are likely to taint signals of neutron detectors – the primary reactor control instrumentation.

In order to better understand gamma radiation in nuclear reactors for the purpose of developing nuclear instrumentation, gamma measurements have been made in two research reactors, the SLOWPOKE-2 (Safe LOW POwer Kritical Experiment) at the Royal Military College of Canada [1] and the ZED-2 (Zero Experimental Deuterium) at the Canadian Nuclear Laboratories [2]. Gamma *dose rates* (in Gy/h) were measured in both reactors at specific reactor locations, using different methods: i) by *dyed polymethylmethacrylate* (PMMA) dosimeters and *silica fibres* for the SLOWPOKE-2, and ii) by a traditional *gamma chamber* for the ZED-2. The methods were simple enough in that the dosimeters or detectors were calibrated in a Co-60 fixed-source gamma cell with a known dose rate before measurements in the reactors. The gamma chamber used in the experiment was an industrially manufactured argon-filled ionisation chamber. The physics behind the dosimeter methods is that a) gamma radiation changes the PMMA's *colour* whose wavelength can be quantified with a spectrophotometer post-irradiation; b) gammas dislodge electrons from silicon atoms to generate *Cherenkov radiation rays* (near infra-red and visible lights) that are carried by the silica fibres to a photomultiplier tube (PMT) to be counted in real-time.

This paper presents the validation of the above gamma measurements using MCNP [3] full-reactor models of the SLOWPOKE-2 and ZED-2 reactors. These models were developed primarily for reactor physics analysis but are capable of tracking reactor *photons* (gammas, X-rays), whose primary origins are, in fact, fission neutrons that interact with reactor materials. Further, photons that are directly created from neutron interactions (*e.g.*, fissions, captures, inelastic scatterings) are referred to as the *primary photons*, to be distinguished with *secondary photons* that are produced as a result of subsequent photon-material interactions. By default, MCNP (version 5) only accounts for these *prompt photons* (both primary and secondary). On the other hand, the *delayed photons*, resulting from decays of fission and activation products, may be populated in some approximate way, which turned out to contribute to a weighty part of total photon effects in nuclear reactors.

2. MCNP Full-Reactor Models

MCNP full-reactor models have been satisfactorily used for full-core neutronics analysis of the SLOWPOKE-2 and ZED-2 reactors, such as for calculating reactivity feedback and core burnup in SLOWPOKE-2 [4], or for designing and validating experiments in ZED-2 [2]. These calculations usually employ the criticality (KCODE) mode, with neutrons alone (MODE N), to obtain k-eff and the distribution of neutron flux and/or fission power. It is possible to include photons in MCNP transport calculations in parallel with neutrons (MODE N P). The SLOWPOKE-2 and ZED-2 reactor models presented below differ in geometry and materials but have the following common features:

- MCNP5 [3] Release 1.40 execution;
- ENDF/B-VII neutron cross-sections for all materials at a uniform temperature (~25°C), and ENDF/B-VI.8 photoatomic data;
- KCODE criticality calculation, with ~200 million neutron histories for k-eff convergence to within 0.1 mk (1 mk = 0.001 Δk/k);
- MODE N P for tracking both neutrons and photons in space and energy;

- Approximate delayed photons either ON or OFF;
- At least, one neutron flux tally (F4:N) at a location of the known measured flux (*e.g.*, detector) required for normalization;
- Several photon tallies at the measurement locations: *flux* (F4:P) with dose function (DF, as of ICRP-74 [5]) for dose rates; *intensity* (*F4:P) in multiple energy intervals (bins) for photon spectra; *heating* (F6:P) – basically, the photon energy deposition in dosimeter/detector materials – for comparison;
- Print of Table 140 (output of neutron and photon activity) for quantification of primary photon sources and verification of approximate delayed photons when included.

1.1 SLOWPOKE-2

Figure 1 shows the MCNP model of a SLOWPOKE-2 reactor, fuelled by LEU (low-enriched uranium) elements, cooled and moderated by light water (H_2O), where the gamma dose rates were measured inside some of the inner and outer irradiation tubes. Fuel elements in the model are axially sectioned to accommodate different burnups (varying from element to element and from section to section in each element), corresponding to a core burnup of 35 kW·a [4] (at about the time of the experiment). The full power of SLOWPOKE (typically, ~20 kW) is calibrated to the maximum thermal flux 10^{12} n/cm^2/s in an inner irradiation tube.

1.2 ZED-2

Figure 2 shows the MCNP model of the experiment setup in ZED-2, consisting of a large aluminium calandria tank containing vertical channels each loaded with five CANDU®-sized fuel bundles. For this experiment, fuel bundles containing either LEU or MOX (mixed [uranium and plutonium] oxides) were loaded in 12 D_2O-cooled and 40 H_2O-cooled channels. Criticality in the ZED-2 reactor was controlled by adjusting the heavy-water (moderator) level in the calandria tank. Although ZED-2 has a gigantic size as compared to a SLOWPOKE-2, its full power is only a fraction of that of the latter, *i.e.*, a few hundred watts only.

The gamma chamber was installed in an aluminum calibration rig located in the moderator at reactor position O9E (Figure 2), at an elevation of 110 cm above the reactor floor. A fission chamber (for neutrons) was installed in the same calibration rig at an elevation of 90 cm. Two rotating reference wheels were symmetrically positioned with respect to the calibration rig at reactor position O9W (Figure 2), at elevations of 100 cm and 110 cm, respectively.

1.3 Delayed photons

Technically, the MCNP method can track only *prompt photons* (*pp*) consisting of the *primary photons* which originate from neutron-nuclear interactions – mostly, fissions (n, f) and inelastic scatterings, and to a much less extent, neutron captures (n, γ) (thus, termed in MCNP as the *photons created from neutrons*), and, the *secondary photons* created from subsequent, but almost instantaneous, photon-material interactions. The *delayed photons* (*dp*) that arise much later from decays of the fission and/or activation products can be approximated by using an in-house MCNP patch, DPERT [6].

Table 1 summarizes the primary photon sources in the SLOWPOKE-2 and ZED-2 reactors operating at powers attained for the respective experiments, *i.e.*, ~20 kW for SLOWPOKE-2 and ~270 W for ZED-2. These data were taken from the MCNP output Table 140 and re-normalized accordingly.

As seen from Table 1, only a few neutron-nuclear reactions contribute to greater than 1% of the total primary photon energy in either reactor. Also given in Table 1 are those conceivable maximum delayed photons that would be fully released in the reactor following an infinitely long operation at the full power, of which over 90% is from the decay of fission products of U-235 and U-238.

SLOWPOKE-2 and ZED-2 reactors normally operate no more than several hours during a day, and multiple extended interruptions are not unusual, and hence, the full (100%) release of delayed photons as presented in Table 1 is very unlikely (as it would be after several days of continuous operation). Since most of the delayed photons in these reactors are from the U-235 fission products, it is reasonable to assume that the total energy release of delayed photons is proportional to the heat release (both betas and gammas) from decays of U-235 fission products, whose dependency on the decay time is illustrated in Figure 3 (based on the ANSI/ANS-5.1-2005 data [7], relative to the full release of 100% at infinite decay time). In an operating reactor, the operation time is equivalent to such a decay time elapsed from the first fission pulse or start-up. It can be seen that ~70% of the maximum delayed photons (70% *dp*) is released in the reactor just after 15 minutes on power, and ~80%-85%*dp* during the experiment in SLOWPOKE-2 (typically, a couple hours on power), which is relatively significant as the inclusion of these delayed photons gives rise to more than 30% increase in the calculated photon results.

The MCNP patch DPERT was used to add the number of primary prompt photons from the conceivable sources, as listed in Table 2, to simulate the primary delayed photons such that their total energy release is preserved [6]. For example, the total release of delayed photons (100%*dp*) from decays of the fission products per U-235 fission is 6.33 MeV/fission, the average energy of the prompt photons emitted from U-235 fissions is 0.93767 MeV/pp, hence, 6.33/0.93767 = 6.75 prompt photons are added to play the role of delayed photons.

2. Results and analysis

For each reactor, the MCNP calculations were performed at two hypothetically extreme states: *prompt photons* (*pp*) only, and *prompt photons* plus 100% *delayed photons* (*pp+dp*), as the measurement data must be between these two states. All calculated flux and energy data were normalized to the detector-measured neutron flux in the reactor at the time of the experiment.

2.1 SLOWPOKE-2

Table 3 summarizes the *calculated* and *measured* radiation data of interest in SLOWPOKE-2. As seen, the calculated dose rates are considerably different than the measured data, namely, more than 3 times that with PMMA dosimeters but only about half that with silica fibres. It was noted by the experimenters that only a few measurements with the PMMA dosimeters were made and these all had *barely reached the lower limit of their dose range*, 1-5 kGy, so their measurement results were too inaccurate. On the other hand, the fibre-measured data were found to be reasonably meaningful when taking into accounts various radiation and optical effects on silica fibres, as discussed below.

Firstly, as a result of the delayed photons being released with the reactor operation (estimated to be ~85% delayed photons during a couple hours of operation, see Figure 3), the dose rates from both prompt and delayed photons at the irradiation sites were estimated to be:

- inner tube: 28.2 ± 0.3 kGy/h (max.) 24.2 ± 0.3 kGy/h (average over 16 cm)
- outer tube: 9.6 ± 0.2 kGy/h (max.) 8.9 ± 0.2 kGy/h (average over 16 cm),

which amount to 55% and 58%, respectively, of the measured values with the silica fibres (cf. 44.3 and 15.4 kGy/h, respectively, see Table 3).

Secondly, dose rates *in air* are usually calculated and quoted but always measured with dosimeters made of *specific materials* (*e.g.*, silica). By using tally F6:P (heating) and calculating such a direct energy deposition per unit mass of silica (which is a *more accurate* dose in silica, Gy = J/kg) and compared to air, it has been found that the photons from neutron captures in silicon appear to marginally increase the dosimeter reading, by a factor of 1.03 at the inner site and 1.06 at the outer site (note that the thermal-to-epithermal neutron flux ratio at an outer site is ~4 times that at an inner site).

Thirdly, the low-energy photons in the reactor caused an inflation of the Cherenkov radiation counts. Figure 4 compares the calibration and measurement photon spectra, of flux and intensity, calculated by MCNP in an approximate gamma cell of Co-60 sources (modeled as a lead-walled cylinder with two gamma peaks at 1.17 MeV and 1.33 MeV, which were smeared due to being tallied in a single bin from 1 to 2 MeV) and at the outer tube of the reactor, respectively. Since only photons of energy above a 195 keV threshold are capable of inducing Cherenkov radiation in silica, the dosimeter reading in the reactor was not consistent with its calibration. Although the Cherenkov-induced photon intensity of the calibration appeared to be larger than that in the reactor (Figure 4 right, so the measurement reading should be lower than it would be), the flux of low-energy photons in the reactor outnumbered the calibration data (Figure 4 left) as they were trapped and guided by silica fibres to the counting device, making the dosimeter reading unpredictably inaccurate (Cherenkov lights and very-low-energy photons are indistinguishable).

2.2 ZED-2

Table 4 summarizes the *calculated* and *measured* radiation data of interest in ZED-2. As expected, the measured dose rate was between those at the two extreme states, without *dp* (or *pp* only) and with 100%*dp* (or *pp*+*dp*). It can be found that an increase in the dose rate due to delay photons was (12.2 – 11.29)/(14.34 – 11.29) ~ 30%, corresponding to just a few minutes after the start-up of ZED-2, indicating the suitability and reliability of gamma chambers for in-reactor measurements.

3. Conclusion

MCNP full-reactor models of SLOWPOKE-2 and ZED-2, categorized as low-power research reactors, have been used for study of gamma radiation, as by-product results from normal neutronics calculations. The delayed photons contributed to as much as 1/3 of the local photon intensity or committed dose rate.

The ion chamber measured data are in good agreement with the calculated results, indicating its reliability for use. However, PMMA and silica fibre dosimeters appeared to be unsuitable for gamma measurements in low-power research reactors. While PMMA dosimeters require longer exposures for better results, silica fibres can produce unpredictable results due to mixing of both low-energy photons and Cherenkov lights.

4. Acknowledgment

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5. References

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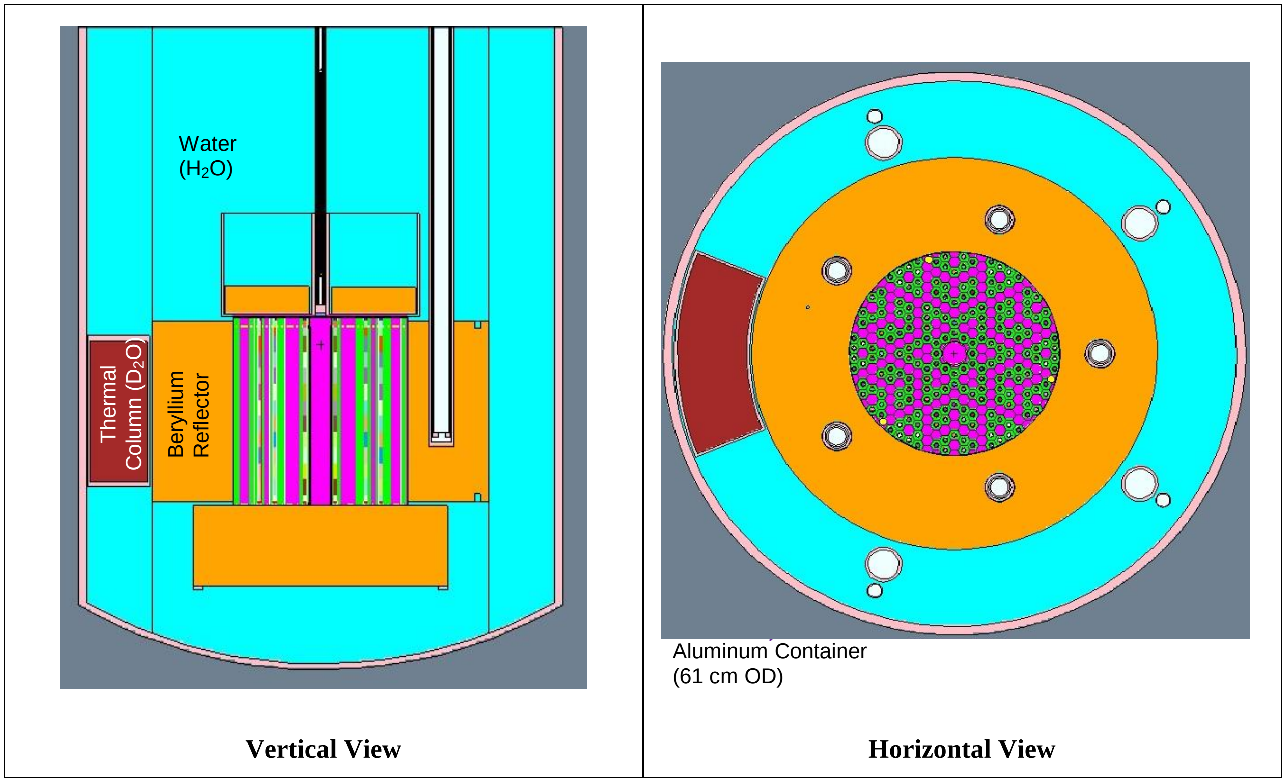

Figure 1 SLOWPOKE-2 model

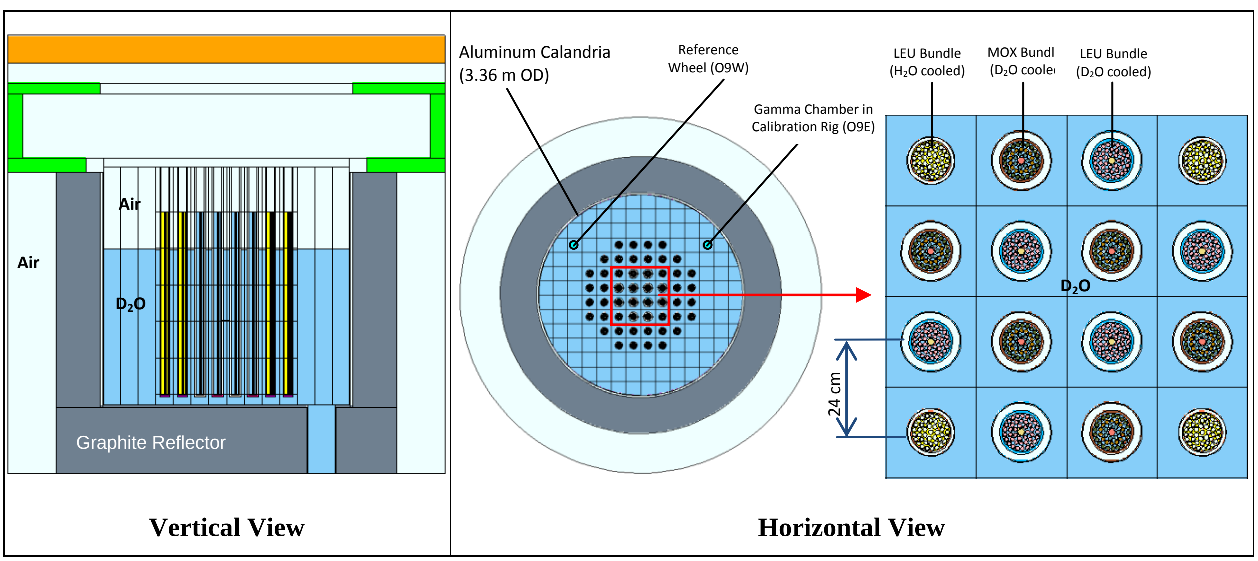

Figure 2 ZED-2 model

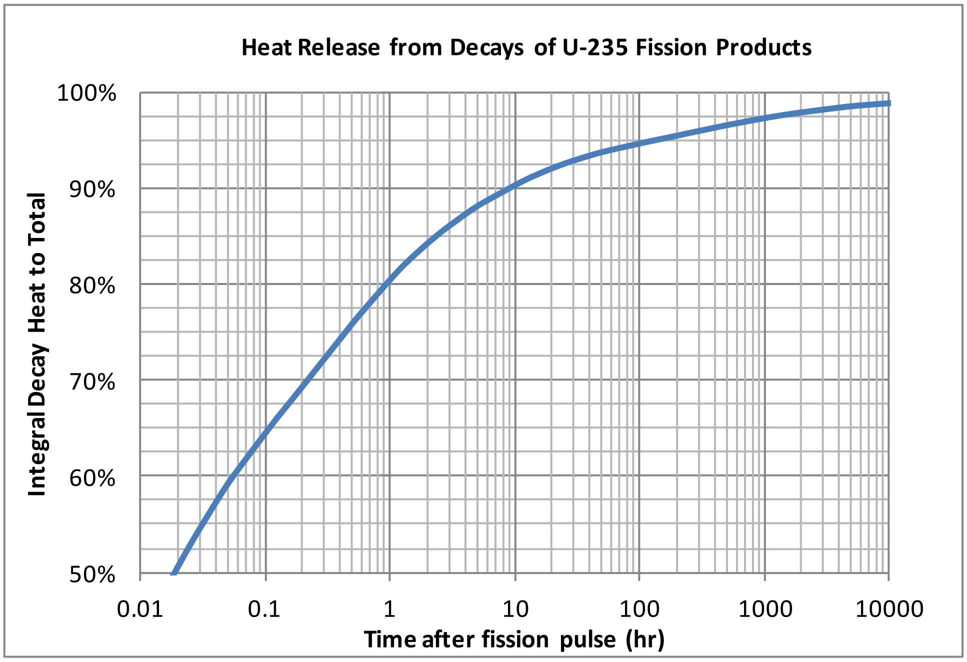

Figure 3 Relative heat release from decays of U-235 fission products vs. decay time [7]

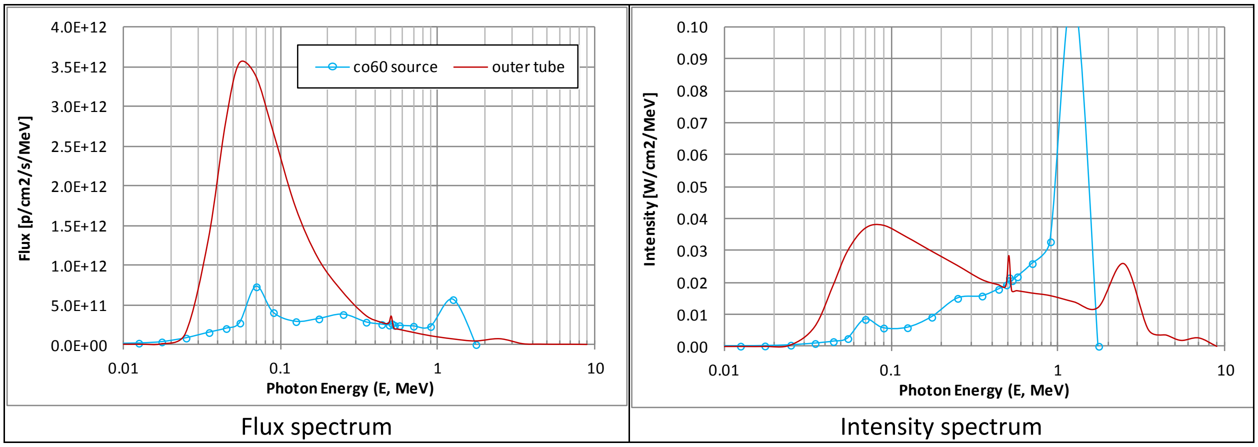

Figure 4 Calibration and measurement photon spectra

Table 1 Primary photon sources in SLOWPOKE-2 and ZED-2 reactors

Neutron-Nuclear Reaction	SLOWPOKE-2		ZED-2		Product to Decay ($T_{1/2}$, total gamma energy release)
	pp (W)	*dp* (W)	*pp* (W)	*dp* (W)	
H-1(n, γ)	273	-	0.6	-	-
H-2(n, s)	-	-	0.1	-	-
Be-9(n, p)	30	-	-	-	-
C-12(n, s)	-	-	0.2	-	-
Al-27(n, γ)	30	7	1.5	0.3	Al-28 (2.25 m,1.78 MeV/capture)
Zr(n, γ)	12	<1	0.2	<0.1	Zr-95 (64.02 d, 0.35 MeV/capture)
Gd(n, γ)	-	-	0.5	<0.1	Gd-159 (18.48 h, 0.05 MeV/capture) Gd-161 (3.66 m, 0.39 MeV/capture)
Dy(n, γ)	-	-	0.3	<0.1	Dy-165 (2.33 h, 0.05 MeV/capture)
U-235 (n, f) & (n, γ)	**870**	**702**	**9.5**	**7.7**	**Fission Products (6.33 MeV/fission)**
U-238 (n, f) & (n, γ)	50	10	5.1	0.5	Fission Products (8.23 MeV/fission) U-239 (23.45 m, 0.24 MeV/capture)
Pu-239 (n, f) & (n, γ)	-	-	0.3	0.2	Fission Products (5.17 MeV/fission)
Sm-149 (n, γ)	8	-	-	-	-
Others	<10	<1	<0.3	<0.1	-
Total energy release (W)	**1280**	**720**	**18.6**	**8.7**	
Average γ energy (MeV/γ)	1.191	1.090	1.101	1.055	

Table 2 Primary delayed photons in SLOWPOKE-2 and ZED-2 reactors

Reaction	Total delayed photon energy(*) (MeV/reaction)	Per-photon energy(**) (MeV/pp)	Number of *pp* added as *dp*
U-234(n, f)	6.13	0.88671	6.91
U-235(n, f)	**6.33**	**0.93767**	**6.75**
U-238(n, f)	8.25	0.88689	9.30
Pu-239(n, f)	5.17	0.87041	5.94
U-238(n, γ)	0.235	4.8063	0.049
Al-27(n, γ)	1.779	~4	0.0068(1)
Zr-94(n, γ)	0.733	2.1076	0.348
Gd-158(n, γ)	0.052	1.8618	0.028
Gd-160(n, γ)	0.388	1.7278	0.225
Dy-164(n, γ)	0.046	1.6216	0.028

(*) ENDF/B-VII neutron data (*http://t2.lanl.gov/data/neutron7.html*).

(**) The average energy of prompt photons emitting from a given reaction type (as from MCNP output table 140).

(1) To add a correct amount of 1.779 MeV for Al-27 capture photons as whose per-photon energy changes with the number of added photons due to a bug in DPERT.

Table 3 Calculated and measured radiation data for SLOWPOKE-2

Location	Core (average)		Inner Tube (max.)		Outer Tube (max.)	
	pp	*pp + dp*	*pp*	*pp + dp*	*pp*	*pp + dp*
Calculated						
Thermal neutron flux (n/cm^2/s)			**1.0E+12**(*)		4.9E+11	
Photon intensity (W/cm^2)	0.666	1.112	0.216	0.342	0.083	0.117
Photon dose rate (kGy/h)			**18.7**	**30.0**	**7.1**	**10.1**
- averaged over 16 cm			**16.2**	**25.6**	**6.6**	**9.3**
Calculated v Measured, fibre			-63%	-42%	-57%	-40%
Measured dose rate (kGy/h)						
- in PMMA(1)			5.43		-	
- in fibre bundle(2), ave/16 cm			**44.3**		**15.4**	

pp – prompt photons only
pp+dp – prompt photons and 100% delayed photons
(*) used for normalization
(1) PMMA – dyed polymethyl methacrylate dosimeter, sized 3.0 x 1.1 x 0.3 cm^3
(2) Fibre bundle containing polyimide-coated silica fibres (∅0.2-mm), 3 fibres in the inner-tube bundle and 100 fibres in the outer-tube bundle.

Table 4 Calculated and measured radiation data for ZED-2

Site	Reference Wheel		Fission Chamber		Gamma Chamber	
	pp	*pp + dp*	*pp*	*pp + dp*	*pp*	*pp + dp*
Neutron Flux (n/cm^2/s)						
Calculated	2.37E+08	2.38E+08			2.23E+08	2.24E+08
Measured	2.43E+08		**2.24E+08**(*)		2.21E+08	
Calculated v Measured	-2.3%	-1.9%			+1.0%	+1.1%
Photon dose rate (Gy/h)						
Calculated					**11.29**	**14.34**
Measured					**12.2**	
Calculated v Measured					-7.5%	+17.5%

(*) used for normalization