REVISED DELAYED PHOTONEUTRON DATA FOR USE IN CANDU-REACTOR ANALYSIS

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ABSTRACT

A new set of delayed-photoneutron parameters for four fissionable nuclides (^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu) is proposed for use in CANDU®-reactor analysis. The new delayed photoneutron yields are all smaller than earlier values. This is especially the case for ^{239}Pu. The new photoneutron yields are very nearly consistent with the calculations Walker and Okazaki made in 1969 as well as the experimental measurements reported in 1973 by Baumann et al. The new photoneutron data are based on a reanalysis of an earlier experiment made by French in AECL's ZED–2 reactor. Since the direct delayed-neutron yield exceeds the delayed-photoneutron yield, the new *total* delayed-neutron yields per fission representing the combination of the direct delayed-neutron and delayed-photoneutron sources are only slightly less than the old yields, despite the significant relative reduction of the photoneutron components when viewed in isolation.

1 INTRODUCTION

Delayed-neutron data play a key role in the dynamic analysis of nuclear-power reactors [1, 2, 3]. The analyses of accident scenarios depend in part on the values of the delayed-neutron parameters used in the analyses. The same delayed-neutron data are used in the design of reactor-control systems.

CANDU reactors, which are heavy-water moderated and cooled, exhibit several fundamentally different sources of neutrons whose emission is delayed significantly relative to the initiating fission event. The more important of these sources are neutrons emitted directly by some decaying fission-product nuclides (^{87}Br and others), and delayed photoneutrons, which are emitted as the result of the D(γ,n) reaction occurring in heavy water when the decay-gamma energies exceed the reaction threshold, $E_\gamma \approx 2.225$ MeV [4]. Photons with energies in excess of this threshold are emitted with varying intensities by some fission products (^{140}La and others) when they decay, and by various transmutation products in structural material and fuel when they decay. The transport of gamma rays to the heavy water, and any subsequent D(γ,n) interactions, takes place nearly instantaneously.[a]

[a] Some *prompt* photoneutrons result from D(γ,n) events caused by energetic photons emitted immediately following nuclear fission or very soon after via radiative neutron capture in the fuel, structural material or heavy water. For example, the ^{238}U(n,γ) reaction is an important source of photons in CANDU reactors with energy in excess of the 2.225-MeV threshold, and so too then of photoneutrons; however, this photoneutron source is delayed relative to fission by only the short time it takes to thermalize a fission neutron and so is customarily considered to be prompt rather delayed.

This paper addresses delayed-photoneutron data applicable to the fission of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu, which are the fissionable nuclides of primary importance in current CANDU fuel cycles. Attention is paid only to the sources of delayed photoneutrons associated with the decay of fission-product nuclides in the fuel. (The source of delayed photoneutrons flowing from photon emission via activation-product decay in nuclear-reactor structural material is not considered in this work.)

Estimates of parameters gleaned from the literature are compared with tabulations for CANDU reactors published in an earlier report by Kugler [5]. A small shortcoming was identified in Kugler's interpretation of the literature on the photoneutron delayed-neutron source: the yield per fission is not the same for all fissionable nuclides; rather, a better approximation is that it is proportional, to within ±25%, to the direct yield of delayed neutrons [1], which varies significantly from one fissionable nuclide to the next. The new estimates of delayed-photoneutron yields were reduced in light of experimental data newer than the Bernstein et al. set [6, 7, 8], which underlies Kugler's tabulations. Since the direct delayed-neutron yield is much greater than the delayed-photoneutron yield, the new *total* delayed-neutron yields per fission representing the combination of the direct delayed-neutron and delayed-photoneutron sources are only slightly smaller than the old yields, despite the significant relative reduction of the photoneutron components when viewed in isolation.

2 DELAYED NEUTRONS FROM THE PHOTODISINTEGRATION OF DEUTERIUM INDUCED BY FISSION-PRODUCT-DECAY GAMMA RAYS

2–A An Overview of Some Earlier Analyses

In contrast to delayed neutrons emitted directly during fission-product decay, the production rate of delayed photoneutrons depends not only on the concentration of fission-product decay precursors in the fuel, but also on the spatial distribution of the decay precursors within the fuel and on the material in the vicinity of the fuel. This is because transport of gamma rays emitted in the fuel to deuterium in the coolant and moderator is required for photoneutron production to occur. Compton-interaction and pair-production processes in the fuel, coolant, moderator and structural material compete for and affect the fate of the gamma-ray photons. From a purist's point of view, it is an *artificial modelling simplification* to couple the delayed photoneutron source to the fission-product-decay process alone. In doing so, assumptions are implicitly made about the nuclear-reactor geometry, the material compositions, and the spatial distribution of fission products in the fuel, since all of these influence gamma-ray transport and thus photoneutron production as well. In addition, the photoneutron source is modelled incorrectly as coinciding spatially with the location of fission-product decay (that is, in the fuel), where, in reality, the photoneutrons are born in the coolant and moderator.

The total direct yield of delayed neutrons from fission-product decay ($\bar{\nu}_{\mathrm{d,dir}}$)[b] greatly exceeds the photoneutron component in CANDU reactors ($\bar{\nu}_{\mathrm{d},\gamma,\mathrm{C}}$); however, the precursors of the photoneutron components tend to be longer-lived. As an extreme example, the decay chain $^{106}\mathrm{Ru} \rightarrow {}^{106}\mathrm{Rh} \xrightarrow{\gamma}$ leads to a photoneutron source with an effective half-life of 371.6 d, although the relative yield

[b]The symbol $\bar{\nu}_{\mathrm{d,dir}}$ is used here to denote the total yield of delayed neutrons generated *directly* from fission-product decay. The additional subscript "dir" is used to distinguish it from the indirect, photoneutron yield ($\bar{\nu}_{\mathrm{d},\gamma}$) which is the subject of this paper. For clarity in certain contexts of discussion $\bar{\nu}_{\mathrm{d},\gamma}$ is further differentiated as follows: the symbol $\bar{\nu}_{\mathrm{d},\gamma,\infty}$ represents photoneutron yield per fission for a speck of fuel in an infinite bath of D_2O, and $\bar{\nu}_{\mathrm{d},\gamma,\mathrm{C}}$, the yield of photoneutrons per average fission in fuel in CANDU-type lattices with heavy-water coolant and moderator. The attenuation and energy degradation of gamma rays before they interact with heavy water is folded into this latter quantity.

from this source is extremely small.[c] The source of delayed neutrons directly emitted during the decay of fission products dominates the photoneutron source for several minutes following abrupt reactor shutdown. The photoneutron source tends to dominate in CANDU reactors thereafter. In the case of abrupt shutdown following a long period of sustained fission of ^{235}U, the photoneutron component accounts for only a small fraction of the delayed-neutron source strength for up to 10 s. The two sources have equal strengths at about 160 s, and the photoneutron source strength dominates thereafter.

Kugler [5] derived his tabulations of photoneutron data from the works of Keepin [1] and French [10]. With the exception of the addition of a low-yield, ninth photoneutron group with a 12.8-d half-life, Keepin's tabulation is based directly on Bernstein et al.'s measurements and interpretations [6, 7, 8]. French measured flux following a rod insertion in AECL's ZED–2 reactor loaded with 28-element, natural-enrichment, UO_2 fuel. Data were recorded from 66 s following rod insertion to nearly 1 h after shutdown. French made a fit of the measured flux data with a flux-decay model that involved the group parameters tabulated by Keepin [1], and so the validity of Bernstein et al.'s photoneutron group parameters is implicitly assumed in French's work, too.

Some criticisms of Bernstein et al.'s now 50-year-old measurements have been made by Baumann et al. [11]. The relative uncertainties in the short-lived photoneutron components derived by Bernstein et al. are much larger than the relative uncertainties in the components yielded directly by fission-product decay. This is because Bernstein et al. gleaned photoneutron yields from the difference of delayed-neutron yields measured in systems with and without deuterium present. In using this experimental method, a high relative error results from the fact that the difference of the two measurements is small, and an accumulation of uncertainty is incurred in making each measurement. Baumann et al. [11] cast doubt on Bernstein et al.'s reported yield for the 2.5-s group; Bernstein et al.'s value is apparently much too high. The pulsed-neutron-beam (chopper) measurements made by Onega et al. [12] provide no evidence whatsoever for the existence of a 2.5-s photoneutron group. Onega et al. also posited the existence of very short-lived delayed-photoneutron groups with half-lives of 4 ms and 74 ms; however, no groups of this sort were observed in Baumann's own pulsed-neutron experiment [11, 13]. The yields of photoneutrons from ^{235}U in an infinite bath of D_2O as determined in the separate experiments of Bernstein et al., Onega et al. and Baumann et al. are listed in Table 1.

Walker and Okazaki [14] inferred the strength of the photoneutron source in a CANDU reactor loaded with 19-element UO_2 fuel from the ^{235}U delayed-gamma emission spectrum measured by Maienschein et al. [15]. Walker and Okazaki's method involved a numerical simulation of gamma-ray transport and subsequent summation of $D(\gamma,n)$ reaction rates. Walker and Okazaki made no corresponding calculations of the emission of delayed photoneutrons corrresponding to the fission of ^{238}U, ^{239}Pu or ^{241}Pu, although, in principle, adjusting the simulated spectrum of delayed fission-product gamma rays and the spatial distribution of the gamma-ray source is all that is required to do so. The calculations made by Walker and Okazaki are subject to error owing to the sharp variation with gamma-ray energy of neutron-production probability in the vicinity of the photoneutron threshold. This problem was mitigated somewhat by their binning energy into groups of approximately 0.5 MeV in width.

[c]Nonetheless, this long-lived photoneutron source, and thus the cumulative fission yields of ^{106}Ru, are of interest in the simulation of residual neutron flux long after reactor shutdown. The cumulative fission yields are, respectively, 0.004023, 0.025311, 0.042851 and 0.062504 for the fission of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu [9]. Note that the ratio of the yields from fission of ^{239}Pu and ^{235}U is 10.65, which implies that there will tend to be a spatial correlation of this CANDU-reactor neutron-source density with fuel irradiation long after reactor shutdown.

The half-life for ^{106}Ru was extracted from ENDF/B–VI tape 204. ^{106}Rh has a half-life of only 29.8 s.

Bernstein et al. [1, 8] believe that in going from one fissionable nuclide to another the number of short-period hard gamma rays goes up or down with the number of delayed neutrons emitted directly via fission-product decay, and thus it loosely follows that

$$\bar{\nu}^{j}_{\mathrm{d},\gamma,\infty} \propto \bar{\nu}^{j}_{\mathrm{d,dir}}. \tag{1}$$

The measurements they made for ^{233}U, ^{235}U and ^{239}Pu support this proportionality hypothesis to within ±25% for an observation period of 120 s following irradiation. A shortcoming is apparent in Kugler's interpretation of the same literature, since in Reference 5 a single value of $\bar{\nu}_{\mathrm{d},\gamma,\mathrm{C}}$ (one appropriate for ^{235}U) is assumed to apply to all four fissionable nuclides. As a result of this (as well as some other sources of error to be discussed later), Kugler's tables effectively overestimate the yield of photoneutrons following fission of ^{239}Pu. If the Bernstein et al. proportionality hypothesis (BPH) is true in general, Kugler's table would also tend to overestimate the yield of photoneutrons following fission of ^{241}Pu, and would underestimate the yield following fission of ^{238}U. For lack of experimental data supporting any other stance, the BPH is assumed to hold in this work.

2–B A Reanalysis of French's Experiment Involving 28-Element Fuel with More Recent Photoneutron-Yield Data

Several sources of uncertainty can be identified in French's method of deriving the delayed photoneutron source strength from measurements made in AECL's ZED–2 reactor [10]:

1. A single value of ϵ is assumed for all fission-product gamma rays with energy above the photoneutron threshold, where ϵ is a correction factor that accounts for gamma-ray degradation and absorption in the fuel as well as leakage from the reactor. This assumption is supported, in part, by the fact that the fuel-escape probability ($P_E \approx 0.3$) is apparently fairly insensitive to variation in gamma-ray energy in the applicable range above the photoneutron threshold [14].

2. Since French's method is unable to resolve well (or at all) any photoneutron source with a time constant less than approximately 60 s, the overall photoneutron yield determined by French's method is sensitive to the *assumed ratio* of the fractional yields of the short-lived components to long-lived components as measured by Bernstein et al. As discussed in Section 2–A, the yield Bernstein et al. reported for the 2.5-s group is apparently much too high.

3. The recording of data apparently started roughly 60 s after rod insertion. Of the six direct delayed-neutron groups, only the two longest-lived contribute significantly to the direct delayed-neutron component after 1 min, and after 90 s the longest-lived group dominates the little that remains of the direct component of the total delayed source. Estimates made by Tuttle of the uncertainties of the fractional group yields for these two groups are 10% for the longest-lived group and 3% for the next-longest-lived group [16, 17]. Thus, a significant uncertainty in inferred absolute photoneutron yield can be attributed to relating the photoneutron component to the residual direct delayed-neutron component that exists 1 min and more after reactor shutdown.

4. The presence of photoneutrons stemming from the decay of fission products of ^{238}U muddies the interpretation of French's experiment. Under the BPH, fission products of ^{238}U may account for approximately 20% of the total photoneutron yield. French made some assumptions

about the similarity of various aspects of the photoneutron sources caused by the decay of fission products of ^{235}U and ^{238}U.

5. The theory of point kinetics is assumed to govern the time dependence of flux measured in the reactor, and the adequacy of this assumption has already been questioned by Jones [18, 19].

Item 2 is likely the most serious of all these criticisms. French's experimental data were reanalyzed by the author using the newer data of Baumann et al. and the same general method as French. As is shown in Table 2, relative to French's original analysis the new estimated total photoneutron yield is reduced by a factor of 3 to $\bar{\nu}_{d,\gamma,C} = 0.00026$ photoneutrons per fission.

The new findings reported here may also explain the difficulty Jones encountered in analyzing data gathered from similar ZED–2 experiments [18, 19]. Jones's analysis used the method of inverse point kinetics [20] to calculate k_{eff} after the rod drop, and the yield of photoneutrons was adjusted to give as constant a value of k_{eff} as possible. At times in excess of 100 s after rod insertion, the best fit to the measured data was obtained with a value of $\bar{\nu}_{d,\gamma,C}$ of 9.5×10^{-4}, whereas prior to 100 s a better fit was obtained when $\bar{\nu}_{d,\gamma,C}$ was reduced by a factor of two. Jones used Bernstein's data in his analysis, and it is interesting to note that Baumann et al.'s data exhibit more weight in the groups with half-life in excess of 140 s than do the Bernstein et al. set. Jones's observation therefore at least qualitatively supports using the newer data of Baumann et al.

Starting with the decay gamma-ray spectra reported by Maienschein et al. [15], Walker and Okazaki evaluated the photoneutron yield as $\bar{\nu}_{d,\gamma,\infty} = 0.0019$ neutrons per fission (see Table 4 of Reference 14). This exceeds the value determined by Baumann et al., $(1.63 \pm 0.03) \times 10^{-3}$ (see Table 1), by only 17%. In an attempt to correct for an energy-yield deficit, Walker and Okazaki multiplied Maienschein et al.'s photon yields at all energies by 1.13. The agreement between the yields calculated by Walker and Okazaki and measured by Baumann et al. would be nearly perfect if this correction had not been made.

Walker and Okazaki recommend reducing the photoneutron yield to $\bar{\nu}_{d,\gamma,C} = 4.7 \times 10^{-4}$ to account for absorption and energy degradation of gamma-rays by 19-element fuel.[d] Walker and Okazaki apparently intended to include the tube-material gamma-ray attenuation factor $T \approx 0.75$ in their calculations, but did not. Multiplying their end result by 0.75 gives an approximate, new result, $\bar{\nu}_{d,\gamma,C} \approx 3.5 \times 10^{-4}$ for 19-element fuel surrounded by power-reactor pressure and calandria tubes. Some MCNP [21] gamma-ray transport calculations were made to help clarify some sources of error and to understand more fully the delayed-photoneutron source and the sensitivity of the photoneutron yield to the variation of fuel-bundle configuration, and also its dependence on pressure-tube and calandria-tube materials. The MCNP simulations made for this work demonstrate that the 19-element fuel configuration is 25% more efficient at generating photoneutrons than is the 28-element configuration,[e] and substituting aluminum for zircaloy in the pressure tube and calandria tube increases the photoneutron-generation efficiency by approximately 15%. Walker and Okazaki's result, extrapolated to 28-element fuel surrounded by aluminum tubes, is therefore $\bar{\nu}_{d,\gamma,C} \approx 3.2 \times 10^{-4}$.

This value is 23% higher than the new estimate derived from the reanalysis of French's experiment involving Baumann et al.'s newer data. Nearly all of this discrepancy (17% out of the 23%) is apparent in the estimates of $\bar{\nu}_{d,\gamma,\infty}$ made independently by Baumann et al. and by Walker

[d]This is the value listed in Table 4 of Reference 14 reduced by an additional 20%, as recommended on page 17 of the same work.

[e]The corresponding efficiency gain of the 19-element configuration relative to the 37-element configuration is approximately 16%.

and Okazaki. The remaining discrepancy may be rooted in some of the difficulties in French's experimental method that were enumerated at the start of this section, or it might be that the various other simplifying assumptions made by Walker and Okazaki resulted in some error in their gamma-ray transport calculation.

Table 2 consolidates for cross-comparison all of the photoneutron yields per fission from the various sources so far discussed in this report. Two photoneutron yields are listed: estimates of photoneutron yield per fission for a speck of ^{235}U in an infinite bath of D_2O, and estimates of photoneutron yield per fission for natural-enrichment UO_2 fuel in CANDU-type lattices (employing standard zirconium fuel channels, heavy-water coolant and moderator and fuel carried in multi-element bundles). The attenuation and energy degradation of gamma rays before they interact with heavy water is folded into this latter quantity.

The ratio of the greatest to the lowest estimate of $\bar{\nu}_{d,\gamma,C}$ listed in Table 2 is 3.6. The lowest value of the six different estimates is recommended here for the reasons summarized below:

- French's experimental data provide nothing that can be used to validate the yield of the photoneutron at very short times, and so French's own estimate of the total photoneutron yield hinged on the accuracy of Bernstein et al.'s yield estimates for the short-lived groups. Bernstein et al.'s yields for the short-lived groups have been invalidated by Baumann et al.

- Observations made by Jones in 1976 add qualitative support to the use of Baumann et al.'s set of photoneutron group yields in place of Bernstein et al.'s set.

- Bernstein et al.'s photoneutron fractional group yields and decay constants were used directly or indirectly in all determinations of $\bar{\nu}_{d,\gamma,C}$, with the exception of the rows labelled "Walker and Okazaki" and "French (Baumann et al. data)", and so all but these two estimates suffer from the same discrepancy.

- The estimate of Walker and Okazaki, which was inferred from the decay-gamma field following neutron irradiation of ^{235}U as measured by Maienschein et al., is in good agreement with the current recommendation (based on French's experiment and Baumann et al.'s newer data) when corrections are made for the differences in fuel configuration.

Tables 3 and 4 summarize the photoneutron parameters now presented for use in CANDU analysis. Large relative uncertainties (ranging from 50% to 75%) are assigned to the four values of $\bar{\nu}^j_{d,\gamma,C}$ for reasons explained in the notes attached to Table 4. The recommended values of $\bar{\nu}^j_{d,\gamma,C}$ for the fissioning nuclides other than ^{235}U now take into account the Bernstein et al. proportionality hypothesis. Kugler's tabulations in Reference 5 do not.

3 SENSITIVITY OF THE PHOTONEUTRON SOURCE TO THE LOCATION OF GAMMA-RAY EMISSION IN THE FUEL

Figure 1 displays some results of simulating the photoneutron source using MCNP version 4B [21]. Four sorts of gamma-ray sources were simulated in a 37-element fuel configuration: three point sources at different locations in the fuel, and one in which the location of photon emission was sampled uniformly from all space occupied by fuel. A strong dependence of photoneutron-generation efficiency on source location is apparent at all gamma energies above the 2.225-MeV reaction threshold. During irradiation of a fuel bundle in a CANDU power reactor, the spatial distribution of fission varies due to the depletion of ^{235}U and the generation and later depletion of ^{239}Pu at rates dependent on local neutron-flux density, and, therefore, on position in the fuel. No attempt has yet been made by the author to fold these effects into the estimates of photoneutron yield per average fission in the fuel. To do so would add a dependence on fuel irradiation to the photoneutron-yield parameters.

Since new gamma-ray line-intensity data are now available, and since improvements have been made in knowledge of fission-product yields, a more fundamental calculation of photoneutron yield (with transport effects included) may be a way to obtain photoneutron yield data with lower associated uncertainty. Sufficient data may also exist to calculate photoneutron yields for ^{238}U, ^{239}Pu and ^{241}Pu for which experimental yield data are scarce or non-existent. Stamatelatos and England made estimates of the photoneutron source using such an approach [22]. They simulated thermal and fast fission of ^{233}U, ^{235}U, ^{238}U and ^{239}Pu. Their calculations, though, are reported only for times in excess of 1 h following simulated reactor shutdown.

4 CONCLUSION

New photoneutron components of the delayed-neutron yield for each of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu are presented for use in CANDU-reactor analysis. The new recommended yield $\bar{\nu}_{d,\gamma,C}$ for ^{235}U is very nearly consistent with the calculations Walker and Okazaki made in 1969. The new value is based on experimental measurements reported in 1973 by Baumann et al., which are apparently superior to the measurements made 25 years earlier by Bernstein et al. The delayed-photoneutron source is much smaller than the direct delayed-neutron source, and so the large relative change in the photoneutron component affects only slightly the estimated total yield from both direct and photoneutron sources.

Provided the gamma-ray-emission spectra of short-lived fission-products are now known sufficiently well, an indirect calculation of the photoneutron source based on a summation of the yields arising from the decay of individual gamma-ray precursors in the fuel may yield better estimates of associated delayed-photoneutron parameters than those gleaned more directly by taking the difference of measurements made with and without deuterium placed in the proximity of irradiated fuel. A calculation of this sort could naturally incorporate the variation in photoneutron yield with gamma-ray source location of the sort displayed in Figure 1. Fuel-average parameters derived in this manner would exhibit a dependence on simulated fuel irradiation. Walker and Okazaki's work along this more analytical line apparently yielded results closer to the truth in 1969 than did the analysis of French's experiment involving Bernstein et al.'s yield data made by French himself in 1973.

The newer set of photoneutron parameters are weighted more heavily towards longer-lived components than are the old. Approximately one-third of the delayed-photoneutron source comes from groups with a half-life in excess of 140 s, and full saturation follows only after many hours of reactor operation.

The yield of delayed photoneutrons arising from fission of ^{239}Pu in a CANDU reactor when calculated using Kugler's parameters is too large by a factor of approximately 5. There are two reasons for this: rather than invoking Bernstein et al.'s proportionality hypothesis, Kugler assumed the same yield of photoneutrons per fission regardless of the fissioning species; and Baumann et al.'s experiments suggest that Kugler's ^{235}U photoneutron yield, which is based upon the Bernstein et al. data, is too high.

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Table 1: Measured and inferred yields of photoneutrons from ^{235}U in an infinite bath of D_2O, as extracted from three different sources

Half-life	$\beta_i \times 10^4$		
	Baumann et al. [11, 13]	Onega et al. [12]	Bernstein et al. [6, 7, 8]
307.6 h	0.0075	0.0050	0.0050
53.0 h	0.0155	0.0103	0.0103
4.4 h	0.0487	0.0323	0.0323
5924.0 s	0.3530	0.2340	0.2340
1620.0	0.3123	0.2070	0.2070
462.1	0.5069	0.3360	0.3360
144.1	1.0560	0.7000	0.7000
>140.0	2.3	1.52	1.52
55.7	0.3	—	—
41.0	—	2.06	2.06
22.7	1.5	—	—
6.22	1.3	—	—
2.50	—	—	6.57
2.30	1.3	—	—
0.074	<0.5	2.5	—
0.0040	<0.3	14.3	—
$\beta \times 10^4 =$	6.7±0.6	20.4	10.16
$\bar{\nu}_{d,\gamma,\infty} \times 10^4 =$	16.3±1.5	49.6	24.73

Notes:

- The relative yields are defined as $\beta_i = \bar{\nu}_{d,\gamma,\infty,i}/\bar{\nu}$ for a speck of ^{235}U in an infinite bath of D_2O. No yield corrections for the gamma-ray shielding effects of fuel and structural material in a CANDU reactor are included here.

- Dashes are used to indicate an absence of a group reported with the tabulated half-life. The physical significance of a missing group, though, is diminished by the fact that the photoneutron groups represent the aggregate effects of gamma-ray emission by many different decaying fission products. Furthermore, the various group parameters were determined in each case by fitting data numerically, and thus large differences in fitted half-life are not always surprising. Of primary importance are the values of photoneutron yield.

- Baumann et al.'s experimental method cannot distinguish a half-life of 2.3 s from 2.5 s, and thus the photoneutron yields of Baumann et al.'s 2.3-s group and Bernstein et al.'s 2.5-s group may be compared [13]. They differ by a factor of 5.

- The entries for the row labelled "> 140.0" were taken from Reference 11.

- In the column listing Baumann et al.'s data, the yields for groups with half-lives in excess of 140 s are those of the Bernstein et al.-data column scaled by the factor $\frac{2.3}{1.52}$, which is the ratio of the entries in the row labelled "> 140 s". The Onega et al.-data column incorporates the same (unscaled) data of Bernstein for groups with half-lives in excess of 140 s. The data in the Bernstein et al. column with half-lives in excess of 140 s were taken from Reference 1. In all three columns, the rows corresponding to half-lives $\leq$ 55.7 s were extracted directly from Reference 11.

Table 2: A comparison of absolute photoneutron yields per fission for two types of uranium fuel in heavy water

Source	$\bar{\nu}_{d,\gamma,\infty}$ (pure ^{235}U)	$\bar{\nu}_{d,\gamma,C}$ (natural U)
Baumann et al. [11]	1.63×10^{-3}	
Onega et al. [12]	4.96×10^{-3}	
Bernstein et al. [6]	2.47×10^{-3}	
Walker and Okazaki [14]	1.9×10^{-3}	3.5×10^{-4}
Jones [18]		9.5×10^{-4}
Tunnicliffe [23]		7.6×10^{-4}
French [10]		8.5×10^{-4}
French (original, reanalyzed)		7.2×10^{-4}
French (Baumann et al. data)		2.6×10^{-4}

Notes:

- Two different types of photoneutron yield are listed in this table: the column labelled "$\bar{\nu}_{d,\gamma,\infty}$ (pure ^{235}U)" lists various estimates of photoneutron yield per fission for a speck of ^{235}U in an infinite bath of D_2O; and the column labelled "$\bar{\nu}_{d,\gamma,C}$ (natural U)" represents the yield of photoneutrons per fission of natural-enrichment UO_2 fuel in CANDU-type lattices with heavy-water coolant and moderator. The attenuation and energy degradation of gamma rays before they interact with heavy water is folded into this latter quantity.

- The tabulated values of $\bar{\nu}_{d,\gamma,C}$ are for 19-, 28- and 37-element bundle geometries and have not been corrected for their dependence on bundle/fuel-channel geometry. The differences in photoneutron-generation efficiencies are discussed in Section 2–B and are all small compared to the variation of the values from one analysis to the next.

- Bernstein et al.'s photoneutron fractional group yields and decay constants were used directly or indirectly in all determinations of $\bar{\nu}_{d,\gamma,C}$ with the exception of the rows labelled "Walker and Okazaki" and "French (Baumann et al. data)".

- All the values of $\bar{\nu}_{d,\gamma,C}$, except the Walker-and-Okazaki result, are based on "rod drop" measurements in a reactor.

Table 3: Recommended delayed-photoneutron half-lives, decay constants and fractional group yields for fission of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu in a CANDU reactor

i	Half-life	λ_i (s^{-1})	a_i
1	307.6 h	6.26×10^{-7}	0.0011
2	53.0 h	3.63×10^{-6}	0.0023
3	4.4 h	4.38×10^{-5}	0.0073
4	5924.0 s	1.17×10^{-4}	0.0527
5	1620.0	4.28×10^{-4}	0.0466
6	462.1	1.50×10^{-3}	0.0757
7	144.1	4.81×10^{-3}	0.1576
8	55.7	1.24×10^{-2}	0.0448
9	22.7	3.05×10^{-2}	0.2239
10	6.22	1.11×10^{-1}	0.1940
11	2.30	3.01×10^{-1}	0.1940

Table 4: Recommended delayed-photoneutron yields for fission of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu in a CANDU reactor

Yield Parameter	Source	^{235}U	^{238}U	^{239}Pu	^{241}Pu
$\bar{\nu}^j_{d,\gamma,C} \times 10^3$	French, Baumann et al., BPH	$0.26 \pm 50\%$	$0.70 \pm 75\%$	$0.10 \pm 75\%$	$0.24 \pm 75\%$
$\bar{\nu}^j_{d,\gamma,C} \times 10^3$	Kugler, Ref. 5	0.85	0.85	0.85	0.85

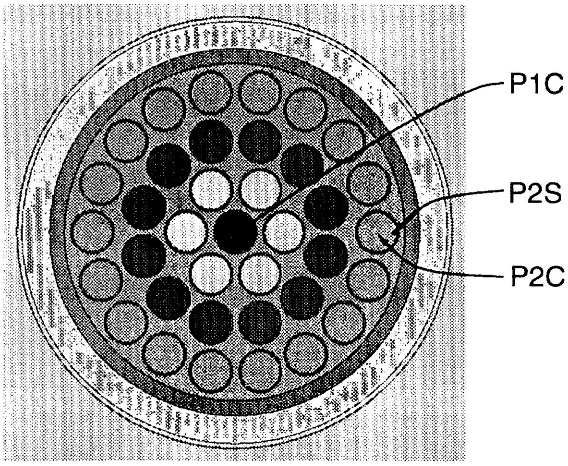
Notes:

- The first row of data contains the new recommended delayed-photoneutron yields per fission. The new yields were obtained from the reanalysis of French's experiment. Kugler's values are included to facilitate comparison.

- The photoneutron yields listed here take into account attenuation and energy degradation of gamma-rays in the fuel and structural material before interacting with the coolant or moderator. The value for ^{235}U is based directly on the reanalysis of French's experiment using Baumann et al.'s data (see Section 2–B).

- The 50% uncertainty estimate in the ^{235}U delayed-photoneutron yield is intended to take into account experimental uncertainty *and* the differences in shielding effects of the pressure-tube and calandria-tube material and of the fuel for various (28- and 37-element) bundle geometries in CANDU reactors and in French's experiment.

- The additional 25% uncertainty applied to the values for the other fissionable nuclides is due to the use of Bernstein et al.'s proportionality hypothesis (BPH) in deducing other delayed-photoneutron yields from that of ^{235}U.



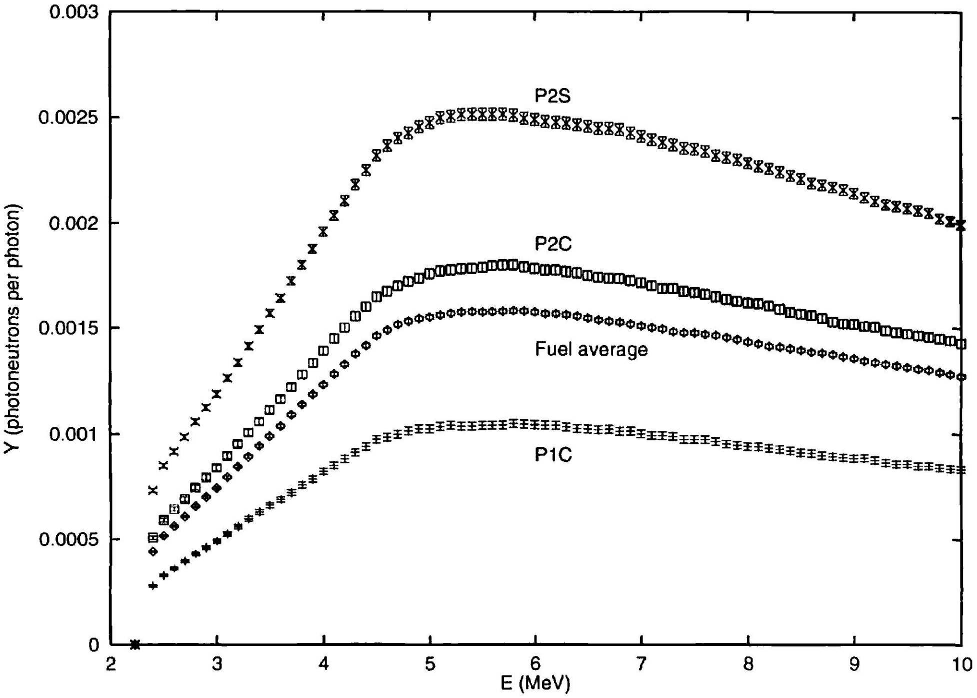


Figure 1: Photoneutron yields arising from monoenergetic, isotropic photon sources at various locations within a 37-element CANDU bundle as calculated using MCNP.