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RECOMMENDED DELAYED PHOTO-NEUTRON DATA FOR USE IN CANDU REACTOR TRANSIENT ANALYSIS

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1. INTRODUCTION

In 1999, changes were recommended to the delayed photo-neutron data for use in CANDU reactor transient analysis following a review by Laughton (1). Previously (2) the fractional group yields for ^{235}U fission measured by Bernstein, as reported by Keepin (5) were used with a value for the absolute yield in a CANDU lattice derived from a measurement by French (6). This absolute yield (0.00085 neutrons per fission) and the distribution by group were assumed to be the same for all fissioning species. On the basis of these assumptions the yield of delayed photo-neutrons was roughly 6% of all delayed neutrons in an equilibrium CANDU core, so it was not expected that the assumptions would lead to major errors.

In his review, Laughton discovered more recent measurements by Baumann of delayed photo neutron yields from ^{235}U fission (7,8). Expressed as fractional group yields these gave a much lower yield at short times after fission than the Bernstein data. When Laughton reanalyzed the measurement of Reference (6) with the Baumann data the absolute yield of delayed photo-neutrons from ^{235}U fission in a CANDU lattice was found to be 0.00026, but it must be noted that the reanalysis could not reproduce the original value of 0.00085 when the Bernstein data was used; a value of 0.00072 was found instead.

For delayed photo-neutrons Laughton's final recommendation was that the fractional group yields and decay constants of Baumann should be used with an absolute yield for ^{235}U fission in a CANDU lattice of 0.00026 neutrons per fission. In addition he recommended that, rather than assuming the same yield for all fissioning species, the hypothesis suggested by Bernstein and described in Reference 5, page 158, should be adopted. This was that the yield of delayed photo-neutrons should be assumed to be directly proportional to the yield of direct delayed neutrons for a given fissioning species. This has the effect of increasing the yield of photo-neutrons for ^{238}U fissions and, more significantly for an equilibrium CANDU core, decreasing the yield for ^{239}Pu fissions.

As an indication of the significance of the effect of the changes recommended, the delayed neutron fraction for an equilibrium CANDU core can be roughly estimated by assuming that the split of fissions is: 50% in ^{235}U, 45% in ^{239}Pu and 5% in ^{238}U. The result is that the average delayed neutron fraction (including direct delayed neutrons as well as delayed photo-neutrons) is reduced by 4.3%, or 0.24 mk compared to that recommended in Reference 2. Of the 0.24 mk, 0.22 mk is due to the selection of Baumann's data over Bernstein's, and 0.02 mk is due to the assumption that the yield of delayed photo-neutrons is proportional to the yield of direct delayed neutrons.

The recommended new values for delayed photo-neutrons were challenged. A program of measurements and calculations was embarked on to help decide between the delayed photo-neutron data sets of Baumann and Bernstein, and to decide on the appropriate way to deal with photo-neutron yields from fission of nuclides other than ^{235}U.

2. RESULTS FROM THE CALCULATIONS

The calculations of yields of delayed photo-neutrons are described in Reference 9. Gamma ray yields were taken from two sources, one giving yields as a function of energy and time following fission of ^{235}U and ^{239}Pu (referred to as the pulsed fission yields), and the other the equilibrium yields for fissions of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu as a function of energy. These sources were used in the Monte Carlo code MCNP to calculate yields of photo-neutrons in two spheres of heavy water, one 1 m in diameter and the other 0.25 m in diameter, as well as in an infinite square lattice of fresh 37-element CANDU fuel at a pitch of 28.575 cm. In the sphere calculations the point sources were located at the centre of the spheres and had no interaction with the gamma rays. In the CANDU lattice the interactions of the gamma rays with the fuel and structural materials in the cells, as well as with the heavy water, were modelled. The important results obtained are summarized in Table 1 and Figure 1.

Table 1 gives the calculated yields of delayed photo-neutrons from both the pulsed and equilibrium data. These are absolute yields, but their greatest value is that the values derived from the equilibrium data give the relative yields from all the fissioning species of interest in CANDU reactors. In addition, the ratio of yields from ^{235}U and ^{239}Pu fissions obtained from the pulsed and equilibrium data agree within 5%, and the absolute yields agree within 15%, which is very satisfactory agreement given that the two sets of data were assembled independently.

Figure 1 shows the calculated time dependence of the delayed photo-neutrons produced following pulsed fission of ^{235}U. Also plotted are the same data derived from the delayed neutron group data of Baumann and Bernstein. The plot clearly shows much better agreement between the calculations of Reference 9 and the group data of Baumann and confirms Baumann's primary criticism of the Bernstein data: that it had too high a yield of neutrons with a 2.5 s half-life. This is important evidence supporting the adoption of the Baumann data, and combined with a review of the measurements on which the Bernstein data were based leads to the conclusion that the Baumann data should be adopted.

3. RESULTS FROM THE MEASUREMENT PROGRAM

The measurements performed were so called "rod drops" in the ZED-2 reactor. They are described in Reference 10 and are very similar to those of French (6), but are superior in that: a better representation of the standard CANDU lattice was used (French used too small a pitch), flux data were recorded throughout the entire transient, and some care was taken to ensure that the measured fluxes could be appropriately analyzed by a point kinetics model.

In brief, the method was to drop an absorbing rod into the centre of a critical ZED-2 core that contained mainly 28-element fuel at the CANDU square pitch of 28.575 cm. Prior to the rod drop the reactor had been operated at constant power for a couple of hours so that most of the delayed neutron emitters were saturated and those that were not (the long lived photo-neutron emitters) could have their degree of saturation accurately calculated. The flux in the reactor was measured by an ion chamber, so placed that its reading was representative of the total neutron population in the reactor, starting just before the rod drop and continuing for about 3000 s. The measured flux transient was then analyzed in two equivalent ways, both based on a point model of the reactor. The first analysis was an inverse point kinetics analysis (11) in which the flux transient was analyzed to yield the reactivity of the core as a function of time. In this case the total yield of the photo-neutrons was varied to ensure a constant reactivity (the rod worth) throughout the transient after the rod drop. This analysis yielded both the worth of the rod and the corresponding total yield of the photo-neutrons. In the second analysis a direct point kinetics calculation of the transient was performed using the worth of the rod and the yield of the photo neutrons derived from the inverse point kinetics analysis. In this analysis changes to the rod worth have a large effect in the early part of the transient, whereas changes to the photo-neutron yield affect the fit at longer times when the longer lived photo-neutrons are the dominant source in the core. Various values of the worth of the photo neutrons were assumed in the calculations to illustrate the sensitivity of the calculated transient to this parameter.

The delayed neutron data required for the point kinetics analysis are effective delayed neutron fractions and decay constants for an average fission in the natural uranium fuelled ZED-2 core. These are expressed by the following formalism. The contributions to the neutron yield, N, from a typical fission in the core are assumed to be prompt and direct delayed neutrons from fission of ^{235}U and ^{238}U plus prompt and delayed photo-neutrons. These contributions are given by:

prompt neutrons: $N_p{}^5 = (1+\delta)^{-1} \times \nu^5 \times (1-\beta^5)$

$N_p{}^8 = \delta(1+\delta)^{-1} \times \nu^8 \times (1-\beta^8)$

$N_p{}^D = \nu^D \times \varepsilon \times (1-\beta^D)$

delayed neutrons: $N_d{}^5 = (1+\delta)^{-1} \times \nu^5 \times W \times \beta^5$

$$N_d^{8} = \delta(1+\delta)^{-1} \times \nu^{8} \times W \times \beta^{8}$$

$$N_d^{D} = \nu^{D} \times \varepsilon \times \beta^{D}$$

where the subscripts p and d refer to prompt and delayed neutrons and the superscripts 5, 8, and D refer to neutrons from ^{235}U, ^{238}U, and D(γ,n)p respectively; δ is the number of ^{238}U fissions per ^{235}U fission (the fast fission ratio), ν is the number of neutrons per fission, β is the delayed fraction, and W is the worth of direct delayed neutrons relative to prompt neutrons (assumed the same for fissions of ^{235}U and ^{238}U).

The parameter ε requires some extra explanation. It accounts for the worth of photo-neutrons relative to prompt neutrons due to their different energy spectrum and location of production, as well as the absorption and energy degradation of gamma-rays in the fuel and structural materials. It is also particularly important to note that in this application ε will account for errors in the assumed values of ν^D and β^D, which are not expected to be accurately known. Thus, this measurement can be expected to produce accurate values of N_d^D, the number of delayed photo-neutrons produced per average fission in natural uranium. In principle ε depends on the fissioning species in that the spectrum of delayed gamma-rays may be different as may the spatial distribution of sources in the bundle. In the measurement, ^{235}U fissions dominate to such an extent that the results can confidently be applied to that nuclide.

Two weaknesses in this formalism are: (1) that there is little point in including prompt photo-neutrons since they contribute only about 0.04% to the neutron yield and may therefore be ignored, and (2) that there is an implicit assumption that the yield of delayed photo-neutrons from fissions of ^{235}U and ^{238}U are the same. The results given in Table 1 indicate that this is not the case, so that N_d^D should be split into two parts as follows:

$$N_d^{D} = ((1+\delta)^{-1} \times \nu^{D5} \times \varepsilon \times \beta^{D5}) + (\delta(1+\delta)^{-1} \times \nu^{D8} \times \varepsilon \times \beta^{D8}).$$

Then, if R is the ratio of the yields of delayed photo-neutrons from ^{235}U and ^{238}U $((\nu^{D5} \times \varepsilon \times \beta^{D5})/(\nu^{D8} \times \varepsilon \times \beta^{D8}))$, the desired separate yields can be calculated as follows:

$$N_d^{D5} = \nu^{D5} \times \varepsilon \times \beta^{D5} = R \times N_d^{D} \times (1+\delta) / (R+\delta), \qquad (1)$$

and

$$N_d^{D8} = \nu^{D8} \times \varepsilon \times \beta^{D8} = N_d^{D} \times (1+\delta) / (R+\delta) \qquad (2)$$

In Reference 10 the first six equations above were used to calculate the delayed neutron fractions for use in the point model analysis. The data for direct delayed neutrons from Reference 3 were used for all analyses, but separate analyses were performed with the Baumann and Bernstein data for delayed photo-neutrons, giving two different values for N_d^D corresponding to the two different values of ε found. The two values of ε, 0.194 with the Baumann data and 0.460 with the Bernstein data, differed significantly, but unfortunately both analyses provided an equally good fit to the measured data.

The reason for this is as follows. As previously mentioned, the main difference between the data sets is that the relative yield of short lived neutrons (half life less than 60 s) is decreased in the Baumann set relative to Bernstein's. Both data sets actually use the same half-lives for the long lived groups, but the relative numbers in them are, of course, greater in the Baumann set. The nature of the measurement and analysis is that ε is mainly sensitive to the need to give the same neutron source strength due to decay of long lived photo-neutron precursors at long times after the rod drop. Hence the much smaller value when the Baumann data is used. At short times after the drop the neutron sources are dominated by direct delayed neutrons, and small differences in the worth of the rod allow a good fit to the data. The corresponding values of ε and rod-worth in the two cases were:

	Baumann	Bernstein
ε	0.194	0.459
Rod-worth	3.69	3.81

Thus if the rod-worth could be established to an accuracy of better than ± 1% by an independent method it would be possible to say which of the data sets was better. Unfortunately no method of sufficient accuracy could be devised.

In Reference 10 it is stated that a change of ± 2% to the values of ε would result in a detectably worse fit to the measured data. This may therefore be taken as the error associated with the measurement of ε, given that the analysis is done with error free delayed neutron parameters. Clearly the result obtained depends strongly on the delayed neutron parameters used.

Using the data given in Reference 10 and equations 1 and 2 above, with a value of R obtained from Table 1 (R=0.798), values of N_d^{D5} and N_d^{D8} are calculated as:

	Baumann	Bernstein
N_d^{D5}	0.000364	0.000861
N_d^{D8}	0.000456	0.00108

It is interesting to compare these values with previous ones. The previously used value (2) was 0.00085 for both ^{235}U and ^{238}U fissions. This was based on a rod drop analysis using Bernstein's data (6), so it is not surprising that it agrees quite well with the values in the Bernstein column above. In Reference 1, Table 4, Laughton recommended values of 0.00026 and 0.00070 for ^{235}U and ^{238}U fissions respectively, based on a reanalysis of the data in Reference 6 using the data of Baumann. The fact that his value for ^{235}U is smaller than that given above in the Baumann column is consistent with the fact that the measurement in Reference 6 was in a lattice having a smaller heavy-water to fuel ratio than in the present case. As already noted the present case is closer to an actual CANDU lattice.

4. COMPARISON OF CALCULATED AND MEASURED YIELDS

Given that a sound basis for selecting the Baumann data over that of Bernstein has already been established, the recommended values for total delayed photo-neutron yield per fission of ^{235}U and ^{238}U respectively in the ZED-2 CANDU lattice are those under the heading "Baumann" in the second table embedded in Section 3 above. The uncertainty associated with those values is roughly estimated at ±11% based on: errors in the measured parameter ε due to the fitting required in the analysis (±2%); errors in the delayed neutron fraction for ^{235}U against which the photo-neutrons are being compared (±3%); and, most significantly, to possible but unknown errors in the Baumann data especially with regard to the split between short and long lived precursors (±10%).

Comparison of these measured values with those in Table 1, calculated for a 37-element CANDU lattice shows the measured values to be 12% higher. The two lattices have almost exactly the same ratio of heavy water to uranium (although the densities of heavy water used in the calculation were those found in an operating power reactor), but the calculated lattice had zirconium pressure and calandria tubes compared to aluminum ones in the measured case. Zirconium is 3 to 4 times more effective than aluminum in causing gamma-rays to lose energy, so further calculations (Reference 12) were performed to establish the magnitude of this effect. These show that the ratio of the yield in the 28-element ZED-2 lattice with aluminum tubes to that in the 37-element lattice with zirconium tubes is 1.15±0.02. The uncertainty associated with the value of this ratio is much smaller than that given in Reference 9 for the yield in the 37-element lattice (±25%) because many systematic errors cancel when the ratio is formed. Using the above ratio to correct the measured value to one appropriate to a power reactor lattice produces very good agreement between measurement and calculation.

5. RECOMMENDED DELAYED PHOTO-NEUTRON DATA

The results of the calculations (9) clearly indicate that the parameters proposed by Baumann for relative yields and half-lives of photo-neutron groups resulting from ^{235}U fission better represent reality than those of Bernstein (see Figure 1). This confirms the conclusion reached by several reviewers of the measurements on which the Bernstein data is based, that the measurements would likely be very inaccurate for short lived photo-neutrons. The calculations also indicate that there are not significant differences in the time dependence of the yields of photo-neutrons following fission pulses of ^{235}U and ^{239}Pu. Therefore it is reasonable to apply the Baumann data to ^{239}Pu fission as well. Approximately 95% of the fissions in an equilibrium core of a natural uranium fuelled CANDU are of ^{235}U and ^{239}Pu. It is therefore clear that insignificant errors will result from using the same data for fissions of ^{238}U and ^{241}Pu and it is recommended that this be done for analysis of such cores. For analysis of other systems the suitability of this recommendation should be reviewed.

The recommended Baumann data for relative yields and half-lives are given in Table 2.

For the absolute total yields of delayed photo-neutrons from fission of ^{235}U and ^{238}U the values derived from the rod drop measurement in ZED-2 analyzed with the Blachot direct delayed neutron data (3) and Baumann photo-neutron data are recommended for use in CANDU analysis after correction for Al rather than Zr tubes by dividing by the factor 1.15. The basis for this is that these values are supported by the calculated total yields, and are consistent with the recommended delayed neutron data because they derive from analysis of a measured transient in a CANDU lattice using that data. Also the measured data include the proper distribution of gamma-ray sources, whereas the calculation used a flat distribution throughout the bundle.

For the other fissioning nuclides of interest it is recommended that the calculated values of yields for the CANDU lattice given in Table 1 under the heading "equilibrium" be used to calculate the yield for the nuclide relative to that for ^{235}U. When this is done values for the total yields per fission can be calculated for each nuclide based on the recommended value for ^{235}U. This leads to the recommended values given in Table 3. The estimated errors include an additional ±5% associated with the calculated yield ratio.

6. SUMMARY

In the introduction to this paper the recommendations of Laughton for new delayed photo-neutron data for CANDU transient analyses (1) were described. Criticisms of these recommendations were made. On the basis of subsequently performed calculations (9) it is now recommended that Laughton's recommendation to use the Baumann data for relative group yields and half lives of delayed photo-neutrons be adopted. However, his recommendations concerning yields of delayed photo-neutrons from fissioning species other than ^{235}U (^{238}U, ^{239}Pu, and ^{241}Pu) are not accepted and are replaced by new recommended values based on the calculations of Reference 9. In addition a new value for the yield of delayed photo-neutrons from fission of ^{235}U is recommended. It is based on new rod drop measurements performed in ZED-2 (10), analyzed using the direct yield data of Reference 3 and the Baumann data.

An important parameter in CANDU transient analyses is the total delayed neutron fraction in an equilibrium core. An approximate estimate of the effect of changes in delayed photo-neutron data on this parameter can be made by assuming that the split of fissions in an equilibrium core is: 50% in ^{235}U, 45% in ^{239}Pu and 5% in ^{238}U and then adding the appropriately weighted contributions of delayed direct and photo-neutrons. When this is done for the old recommended data (2), for Laughton's recommended data, and for the data recommended in this report, it is found that Laughton's recommendations reduced the "old' delayed fraction by 0.24 mk or 4.3% whereas the present recommendations reduce it by 0.23 mk or 4.0%. These reductions should be viewed in the context of the errors associated with the direct delayed neutron fractions of ±3% and ±4% for ^{235}U and ^{239}Pu respectively.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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Table 1 Delayed Photo-neutron Yields per Fission as Computed by MCNP

System	Pulsed		Equilibrium				
	^{235}U	^{239}Pu	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu
37 NU CANDU	3.19E-04	2.09E-04	2.93E-04	3.67E-04	1.84E-04	2.11E-04	2.58E-04
0.25 m Sphere	6.87E-04	4.56E-04	6.53E-04	8.24E-04	4.16E-04	4.78E-04	5.86E-04
1.0 m Sphere	1.28E-03	8.35E-04	1.18E-03	1.48E-03	7.37E-04	8.48E-04	1.04E-03

Table 2 Recommended Delayed Photo-neutron Data: Relative Group Yields and Half-lives

Group #	Fractional Group Yield	Half Life
1	0.0011	307.6 h
2	0.0023	53.0 h
3	0.0073	4.4 h
4	0.0527	5924.0 s
5	0.0466	1620
6	0.0757	462.1
7	0.1576	144.1
8	0.0448	55.7
9	0.2239	22.7
10	0.1940	6.22
11	0.1940	2.3

Table 3 Recommended Delayed Photo-neutron Data for a CANDU Lattice

Yield Parameter	^{235}U	^{238}U	^{239}Pu	^{241}Pu
Delayed Yield, ν_d (per fission)	0.000317 (±11%)	0.000397 (±12%)	0.000199 (±12%)	0.000279 (±14%)
Delayed Fraction, β (mk)	0.130	0.140	0.069	0.095

Notes:

- The total neutron yields per fission, ν, required to calculate delayed fractions, were taken from ENDF/B-VI: 2.4338 for ^{235}U, 2.871 for ^{239}Pu, 2.945 for ^{241}Pu, and 2.8415 for ^{238}U.
- The errors are rough estimates, made as described in the text.

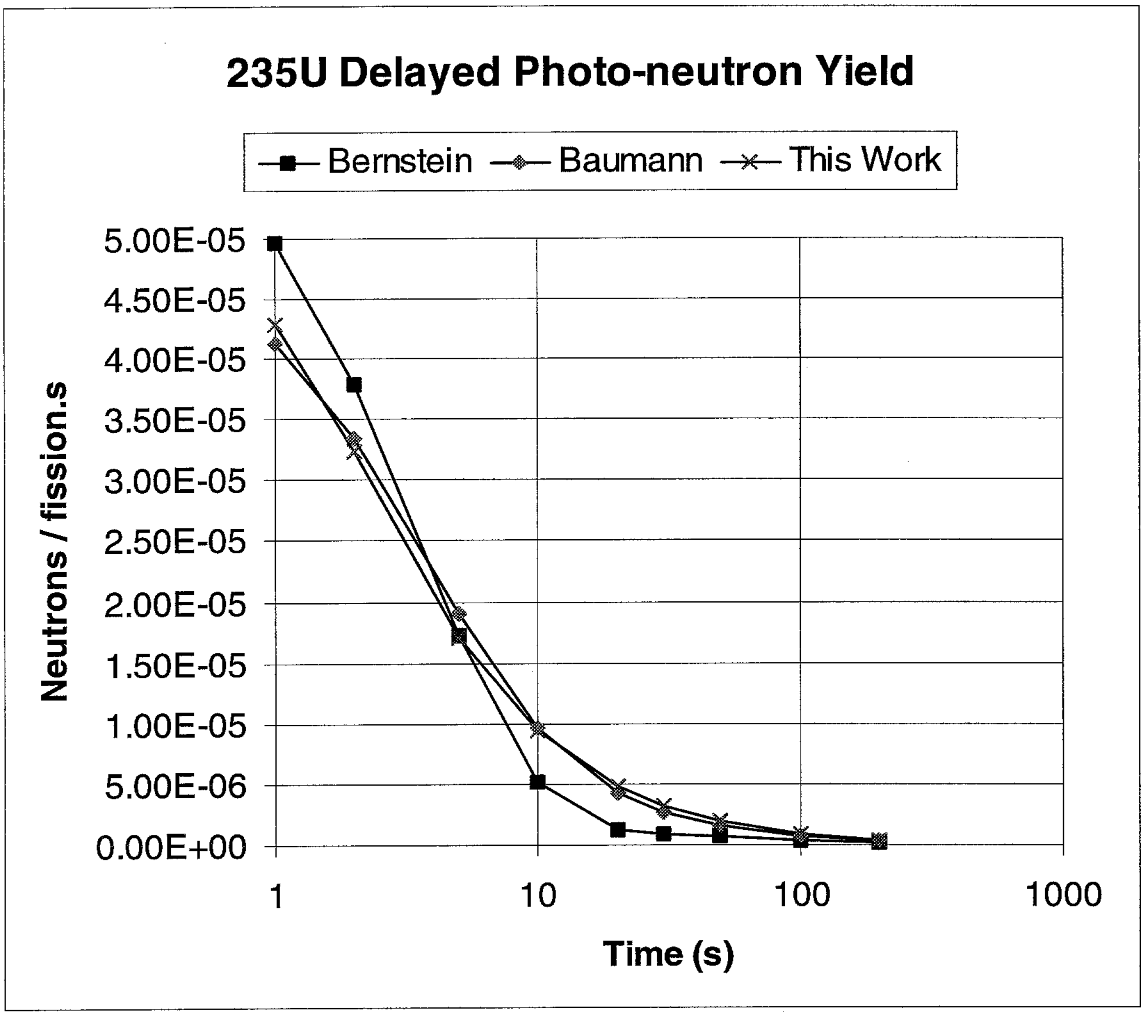

Figure 1

Comparison of the Time-Dependence of the Neutron Yield from a ^{235}U Fission Pulse in an Effectively Infinite D_2O Bath Calculated in this Work with that Arising from the Delayed Photo-Neutron Data of Baumann and Bernstein. The integrated yields have been normalized to the same value.