A REVIEW OF DELAYED NEUTRON DATA FOR CALCULATING EFFECTIVE DELAYED NEUTRON FRACTIONS.

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ABSTRACT

The accuracy of calculations of the effective delayed neutron fraction, β_{eff}, for systems fuelled with uranium and plutonium is discussed. A target accuracy of ± 3% has been proposed and the recommended data are examined relative to this target. The basis for the assessment is a comparison between measured and calculated values of β_{eff} in thermal and fast critical systems. The accuracy of the β_{eff} measurements is reviewed and the effects of possible systematic errors associated with a particular series of measurements is considered.

The accuracy of current fission product precursor summation calculations is summarised first and it is concluded that these calculations are not sufficiently accurate for their use as a source of delayed neutron yield values for the primary fissioning isotopes. Indeed, it is suggested that the measured delayed neutron yield data should be used in the evaluation of fission product yields.

The thermal and fast reactor spectrum averaged values of the total delayed neutron yields for ^{235}U, ^{238}U and ^{239}Pu are reviewed. Values of the total delayed neutron yields recommended for the calculation of β_{eff} have been described in [1] and are summarised here. Also the recommended 8 group time dependence representation [2] and energy spectra [3] are briefly summarised.

1. INTRODUCTION

The accuracy of the yield and decay data for individual fission product isotopes has improved during the past decade, but for β_{eff} calculations reliance must still be placed on macroscopic measurements of the yield data for the major isotopes and validation of the data using reactor measurements of β_{eff}. Indeed, it is by adjusting the yield data to improve the agreement with measured values of β_{eff} that the most suitable data are obtained.

The delayed neutron yield data for ^{235}U, ^{238}U and ^{239}Pu recommended for use in calculations of the effective delayed neutron fraction, β_{eff}, in conventional thermal and fast reactors, has been reviewed in [1] and are summarised and discussed here. The accuracy of calculations of β_{eff} is assessed on the basis of the agreement between calculated values and the values measured in thermal and fast critical systems.

The form proposed by Spriggs, Campbell and Piksaikin [2] for the representation of the time dependence of delayed neutron emission is an 8 group model with a fixed set of half-lives. These are based on the half-lives of the dominant precursors, being the half-lives of ^{87}Br, ^{137}I and ^{88}Br for the three longest lived groups. Relative abundances for the 8 groups have been obtained by the authors by refitting the chosen sets of previously measured and analysed data. The criteria used for selecting the preferred sets are described by the authors.

Campbell and Spriggs [3] have calculated emission spectra for the delayed neutrons in each of the 8 groups and for each fissioning system by means of fission product precursor summation calculations.

It is relative to these recommended sets of data that the accuracy of reactor calculations of β_{eff} is reviewed.

2. THE STATUS OF THE RESULTS OF SUMMATION CALCULATIONS

2.1. ENERGY DEPENDENCE OF TOTAL DELAYED NEUTRON YIELDS

The measurements of β_{eff} made on reactor facilities do not provide accurate information on the energy dependence of yields. The differences between the average values for thermal spectrum and fast spectrum systems are hardly significant, being of the order of 1%. Accurate information on the energy dependence would be very helpful and enable the thermal and fast spectrum values to be interrelated and extrapolation to be made from the measured values to systems with different spectra.

The energy dependent measurements made by Krick and Evans (1972) [4] gave the following increases in the total yield in a 1 MeV interval:

U-233 2.2% (±0.6%)
U-235 0.6% (±1.0%)
Pu-239 2.0% (±0.5%)

On the basis of a fit to the mean half-life of precursors and the correlation between total yield and mean half-life for fast neutrons Piksaikin et al (2002 and private communication) [5] derived the following energy dependences based on this systematics approach:

U-233 2.50% (±0.85%)
U-235 1.50% (±0.96%)
Pu-239 4.90% (±1.36%)

There are other theoretical models, such as that of Lendel *et al* (1986) [6] which has been used by Fort and co-workers [7] to derive the energy dependence adopted in the JEF-2.2 nuclear data library.

The variation of the total yield through the resonance region is another aspect which has been studied by Fort and Long (1989) [7] and, more recently, by Ohsawa and Oyama (1999) [8]. The uncertainty about the possible variations through resonances is one of the factors which prevents a clear conclusion being reached about the relationship between thermal and fast spectrum yields.

The energy dependence of total yields is not well established. More measurements are needed, in particular in the energy range below 1 MeV. Nevertheless, the differences between thermal and fast reactor spectrum averaged values would be expected to be about 1% only.

The differences between the thermal and fast energy values obtained in summation calculations are outside these limits of uncertainty. In their calculations Wilson and England (2002) [9] (using the fission product yield data of England and Rider, 1994 [10]) obtain for ^{235}U a fast spectrum value 6.3% higher than the thermal value, and for ^{239}Pu a value 12% lower. These results are in contrast with the results of the summation calculations carried out by Mills (1999) [11] using the JEF-2.2 decay data and fission yields. He obtained fast spectrum yields 12% larger than the thermal yields for both ^{235}U and ^{239}Pu. In his more recent calculations Mills (2002) [12] has used his latest evaluation of fission product yields and obtains differences between the fast and thermal delayed neutron yields of 18% and 16%, respectively, for ^{235}U and ^{239}Pu. The reason for these large differences between thermal and fast spectrum values should be investigated.

2.2 TIME DEPENDENCE

Figure 1 presents the period-reactivity relationship calculated using different data sets for the time dependence of delayed neutrons produced in thermal fission of ^{235}U. The reference calculation uses the recommended data [2] of Keepin (1957) [13]. It is seen that using the time dependent data directly measured by other authors in either thermal or fast spectra (Saleh, 1997 [14]; Synetos and Williams, 1983 [15]; Charlton, 1999 [16], Keepin fast [13]) gives relationships which agree to within about ±5% with the reference curve calculated using the Keepin thermal data. The curve based on the summation calculation data of Mills (1995) [11] is also within about 5%. However, the summation results of Mills are less good for other fissioning systems. The curves based on the summation calculations using ENDF/B-VI fission product yield data (Brady and England [17], Wilson and England [18, 10]) are in poorer agreement, with discrepancies of about 10%. Furthermore the curve calculated using the latest Wilson and England (2002) [10] summation calculation data isn't significantly better than the earlier summation calculations (and for some fissioning systems it is worse).

Results obtained using Keepin's (1957) data set have been assumed as reference.

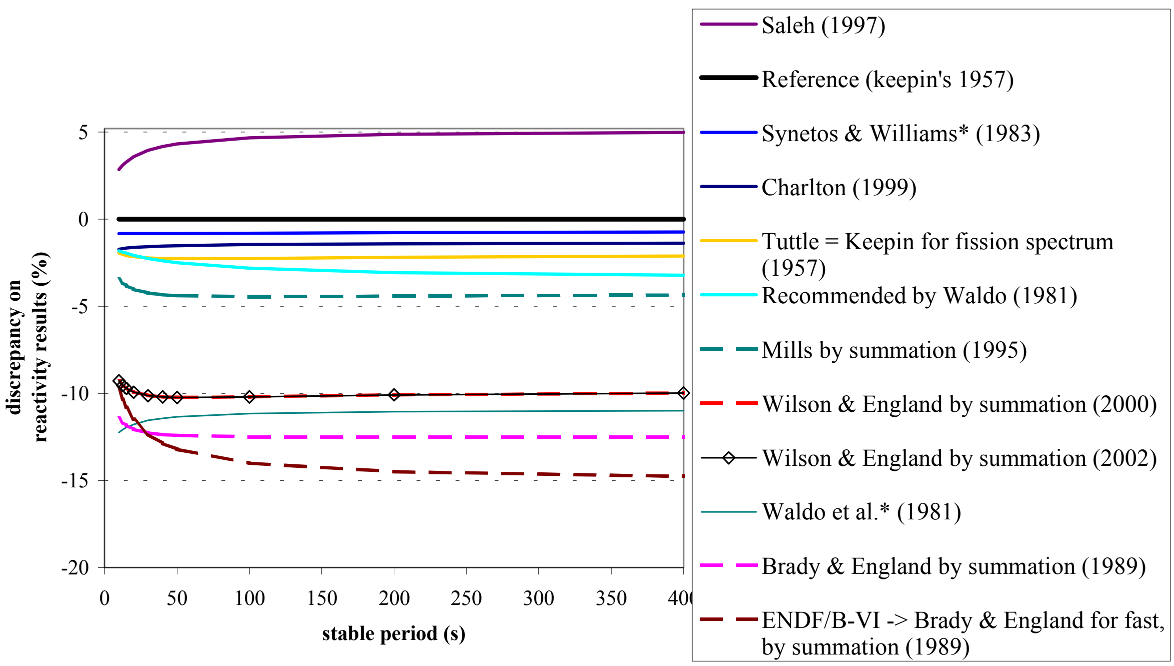

Fig. 1. Reactivity discrepancy relevant to stable period measurement analyses obtained using different data in U235Th critical systems.

An 8 time-group model has been proposed for representing the time dependence of delayed neutron emission. In this model the same set of group half-lives is used for all incident neutron energies and fissioning isotopes. The contributions to the first three groups are dominated by just three fission product precursor isotopes:

Group 1.	Br-87	half-life 55.6 s
Group 2.	I-137	half-life 24.5 s
Group 3.	Br-88	half-life 16.3 s

Analyses of time dependent delayed neutron yield measurements give information about the relative values of these precursor yields. Piksaikin et al. (2002) [5] have made measurements of the time dependence for ^{235}U and ^{239}Pu from epi-thermal (2.8 eV) to about 5 MeV. They have then analysed the data to obtain the relative abundances in the 8 groups. A regression analysis of the incident neutron energy dependence of the relative abundances gives the following energy variations for the first three groups:

Table I. Comparison of the difference between the fast and thermal relative abundances obtained in summation calculations by Wilson and England and the energy variation measured by Piksaikin et al.

		Slope in percent per MeV. Piksaikin et al [5]	s.d. (in percent) Piksaikin et al		Percent difference between fast and thermal relative abundances (Wilson and England [10])
Group 1.	Br-87	+3.0%	± 0.9%		-4.6%
Group 2.	I-137	-4.3%	± 1.0%		-23%
Group 3.	Br-88	-1.4%	± 1.7%		+7.0%

We see that the differences between the fast and thermal relative abundances obtained in the summation calculations made by Wilson and England are well outside the uncertainties on the energy variation measured by Piksaikin et al.

It is suggested that the variation obtained in measurements such as those of Piksaikin et al should be taken into account in evaluations of precursor yields. An approach to the derivation of fission product yield information is presented in the paper by Isaev et al. (2002) [20].

Summation calculations are, nevertheless, a useful source of data for unmeasured or poorly measured fissioning systems. Summation calculations do provide energy spectra for the delayed neutrons and the spectra have been obtained in this way, for the 8 group representation of time dependence, by Campbell and Spriggs [3].

3. THE PROGRAMMES OF BETA-EFFECTIVE MEASUREMENTS

Two complementary series of fast reactor benchmark experiments have been carried out, one in the fast critical facility MASURCA (France) and the other in the facility FCA (Japan) (Okajima *et al,* 2002, [21]). These programmes differ from previous measurements in that in each assembly several different techniques were used and different teams carried out the measurements. Two assemblies were studied in MASURCA, R2 and ZONA2, and three in FCA, XIX-1, XIX-2 and XIX-3. These five assemblies were designed to provide reference values of β_{eff} suitable for validating the delayed neutron data for ^{235}U, ^{238}U and ^{239}Pu in fast reactor spectra.

The benchmark measurements also provide an insight into the accuracy of individual methods. The groups which participated in these fast reactor benchmark experiments were: CEA/Cadarache (France), IPPE/Obninsk (Russia), JAERI (Japan), KAERI (Korea), LANL (USA) and Nagoya Univ. (Japan). The techniques used were: Cf source; Noise; Rossi-α; Modified Bennet and Nelson Number.

Two groups carried out measurements using the Cf source technique. The values of β_{eff} they measured in MASURCA R2 differ by a surprising 5%, the estimated uncertainty being a standard deviation of ± 3%. The derivation of the value of β_{eff} from the parameters which are measured involves calculated correction factors, such as the relationship between the measured fission rate and the average fission rate in the reactor (although these calculated factors can be adjusted on the basis of a comparison between measured and calculated fission rate scans). β_{eff} can be written in the form Pm.Pc, where Pm denotes the measured part and Pc the calculated part. In the case of the two Cf source measurements made in R2 the values of Pm differ by 4% and Pc by 1%. The two Cf source measurements made in ZONA2 are in better agreement, the values of Pm differing by 2% and Pc by 1% giving β_{eff} values which differ by 3%. In the FCA series of experiments two teams again made measurements. In this case the same values of Pc were used by both teams and the Pm values differed by 4% in XIX-1, and by 2% in XIX-2 and XIX-3. The mean values differ from the means of all the measurements by 2% to 3%. Bearing in mind that there are additional sources of error common to all the Cf source measurements made in a core an uncertainty estimate of ± 3% for this technique is perhaps optimistic.

The Rossi-alpha measurement made in R2 comprised measurements made at two different reactivity levels and gave values which differ by 3%. There are additional sources of uncertainty common to both measurements, arising from both the measured and calculated factors. A measurement was also made in FCA XIX-1 and it gave a value 4% higher than the mean value of the measurements made in this core. Again an uncertainty estimate of ± 3% seems optimistic.

Measurements made using the noise technique can be compared with the mean values of the measurements made using different techniques and the agreement is consistent with an estimated uncertainty of about ± 2.5%, provided that there are not errors common to all of the techniques. (The Diven factor is common to all excepting the Cf source technique and it is estimated to introduce an uncertainty in measured β_{eff} values of about ± 1.3%.) We note, however, that a much smaller uncertainty than this figure of ± 2.5% is attributed to the value of β_{eff} derived by noise measurements made in the thermal spectrum MISTRAL cores (± 1.6%) studied in the EOLE facility at Cadarache (Litaize and Santamarina, 2001 [22]).

Further intercomparisons of the different techniques would be helpful in giving confidence in the use of the earlier fast reactor measurements made in SNEAK (Fischer, 1977, [23]) and ZPR (McKnight, Internal ANL document [24]), and the associated uncertainty estimates, where a single technique (Cf source or noise) was used. There is an indication that the measurements made in SNEAK and ZPR are about 2% higher than the average of the measurements in the benchmark series [1].

The agreement between the measured and calculated β_{eff} values is good for the benchmark series, within about ± 3% for the data in the current nuclear data libraries, ENDF/B-VI, JEF-2.2 and JENDL-3.2. However, the ENDF/B-VI yield data underestimate the β_{eff} values measured in those MOX fuelled SNEAK and ZPR cores which have a high dependence on ^{238}U.

Fort et al [25] have carried out an adjustment study using the JEF-2.2 data. Agreement between measurement and calculation is excellent for the benchmark series and for the SNEAK and ZPR cores, and also for the thermal spectrum systems included in the study, on average well within the target uncertainty of ± 3%. They have made small adjustments to the total yield data in JEF-2.2 so as to improve the overall agreement between measurement and calculation.

Sakurai and Okajima [26] have also carried out an adjustment study, in this case based on the benchmark series of experiments (together with a thermal spectrum system) and using JENDL-3.2 total yield data. They also find satisfactory agreement for the JENDL-3.2 data. The total yield data for ^{238}U in JEF-2.2 were adopted from JENDL whereas the total yields for ^{235}U and ^{239}Pu are about 3% smaller in JENDL-3.2 than in JEF-2.2. Following adjustment the yields are also about 3% smaller than the adjusted values of Fort et al [25]. The reason for the difference is the inclusion of the SNEAK and ZPR measurements in the study by Fort et al. and the use of different values for some of the measurements in the benchmark series (following their reassessment of the values and uncertainties). The 3% differences perhaps call into question the overall uncertainty estimation. In reference [1] a weighted average of these two sets of adjusted values was adopted, taking into account, also, the results of some recent direct measurements of total yields.

Several measurements have been made in thermal spectrum systems. In the EOLE facility at Cadarache the uranium fuelled system, MISTRAL-1, and the MOX fuelled system, MISTRAL-2 have been studied (Litaize and Santamarina, 2001, [22]) and the uncertainty estimates given for these β_{eff} measurements are small, ± 1.6%. Measurements were made in Japan in the 1980s in the SHE series of experiments (Kaneko *et al*, 1988, [27]) and the analysis of these resulted in a thermal spectrum value for the ^{235}U delayed neutron fraction having an estimated uncertainty of ± 1.2%. Measurements have also been made in uranium and plutonium fuelled thermal spectrum systems in the TCA facility in Japan (Nakajima, 1999 [28]). The β_{eff} measurement made in the uranium fuelled system has an estimated uncertainty of 2.2% and the ^{235}U yield value appears to be significantly lower than that derived from the SHE series of measurements. The specifications of these measurements have not been published and so no detailed intercomparison of the results has been possible.

4. EVALUATIONS OF TOTAL DELAYED NEUTRON YIELDS.

The yield data in the major nuclear data libraries are summarised and compared with other recommendations, including the data derived in adjustment studies. In Table II we compare thermal and fast spectrum averaged values of the delayed neutron yields derived from various sources. Following the values calculated from the data in JEF-2.2, JENDL-3.2 and ENDF/B-VI the values recommended by Tuttle (1975 and 1979) [29, 30] and by Blachot *et al* (1990) [31] are given. These recommendations were based on the direct measurements of total yields. It is not always clear for what mean energy the fast spectrum values given in an evaluation are defined. The fast reactor spectrum averaged values for ^{235}U and ^{239}Pu (given above, for the evaluated data libraries) correspond to a mean energy of about 200 keV, but there is a wide variation in the mean energies of the different systems included in the adjustment studies. Also included in the Table are the fast reactor spectrum averaged values obtained by D'Angelo (1990) [32] in an integral measurement adjustment study made to fit the SNEAK and ZPR measurements. The value obtained by Kaneko *et al* (1988) [27] for ^{235}U thermal, on the basis of the SHE integral measurements, is also given (beta = 0.00677 ± 0.00008, and assuming ν_t = 2.4367 ± 0.0005). This has a very small standard deviation of 1.2%.

Some recent measurements of total yields have also been included in Table II. These are the measurements made by Piksaikin *et al*, IPPE, (1997) [33] and Parish *et al*, Texas A+M, (1997) [14] for ^{235}U, and by Borzakov *et al*, Dubna, (1997) [34] for ^{239}Pu thermal. (The quoted fast spectrum values for ^{235}U are based on these measurements with an adjustment for differences in energy so as to relate to 200 keV.) The measurement for ^{238}U by Piksaikin et al (2002) [35] is an average for the plateau region of first chance fission (3 to 5 MeV). The reactor spectrum averaged value could be about 2% smaller because of the contribution from second chance fission.

Finally the table includes the values derived in reference [1] from the adjusted data obtained in the studies carried out by Fort *et al* [25] and by Sakurai and Okajima [26]. Both of these studies have resulted in yield values for ^{238}U substantially higher than the ENDF/B-VI data (9.3% ± 2.4% and 6.3% ± 3.6% higher, respectively). The weighted reactor spectrum averaged value is 0.0465 and this was chosen as the recommended value in [1]. Differences in reactor spectra result in variations of about ±1% in the averaged yield for ^{238}U but the variations are smaller for ^{235}U and ^{239}Pu.

Table II. Thermal and fast reactor spectrum averaged values.

	U-235 thermal	U-235 fast	U-238 fast	Pu-239 thermal	Pu-239 fast
JEF-2.2	0.01654	0.01658	0.0468 *	0.00648	0.00646
ENDF/B-VI	0.01670	0.01667	0.0429	0.00645	0.00644
JENDL-3.2	0.0160	0.0161	0.0471 *	0.00622	0.00627
Tuttle (1975)	0.01654 ±2.5%	0.01714 ±1.3%	0.0451 ±1.4%	0.00624 ±3.8%	0.00664 ±2.0%
Tuttle (1979)	0.01621 ±3.1%	0.01673 ±2.1%	0.0439 ±2.3%	0.00628 ±6.0%	0.00630 ±2.5%
Blachot (1990)	0.0166 ±3.0%	0.0166 ±3.0%	0.045 ± 4.5%	0.00654 ±4.0%	0.00654 ±4.0%
D'Angelo ('90)		0.0165 ±2.0%	0.0457 ±3.8%		0.0066 ±2.9%
Kaneko(1988)	0.01650 ±1.2%				
Piksaikin ('97)		0.0168 ±5%**			
Parish (1997)	0.0159 ±2.5%	0.0167 ±4.8%			
Borzakov('97)				0.00686 ±5%	
Piksaikin ('02)			0.0461 ± 3.9%		
Sakurai and Okajima ('02)	0.01586 ± 1.8%	0.0160 ± 1.8%	0.0456 ± 3.6%	0.00638 ± 3.6%	0.00642 ± 3.6%
Fort *et al* *** (2002)	0.01621 ± 1.3%	0.01658 ± 1.6%	0.0469 ± 2.4%	0.00651 ± 1.7%	0.00656 ± 2.6%
Recommended	0.0162	0.0163	0.0465	0.00650	0.00651
Difference from Tuttle (1979)	0%	-2.6%	+5.6%	+3.4%	+3.2%

(The delayed neutron data for ^{238}U in JEF-2.2 were adopted from JENDL-3.2. The value of 0.0468 is an average for the cores studied by Fort et al. The value used by Okajima et al, starting from the same energy dependent data, is 0.0471, which is the average value for the FCA XIX cores.)*
*(** The ^{235}U fast value quoted for Piksaikin et al (1997) is the value measured at 1.165 MeV (0.01709) reduced by 1.9% on the assumption of a rate of increase of 2% per MeV below this energy (Tuttle's estimate of the variation). The ^{238}U value of Piksaikin et al (2002) is an average for the range 3-5 MeV)*
*(*** The uncertainties given here are relative and do not take into account all sources of uncertainty.)*

Reductions to the ^{235}U thermal yield value are proposed both by Fort *et al* and by Sakurai and Okajima, based on their analyses of the MISTRAL-1 and the TCA measurements, respectively. In deriving an average of these adjusted values we have also taken into account the higher value derived by Kaneko et al (1988) [27] on the basis of the SHE programme of measurements. (This has been given a low weight in the adjustment study carried out by Fort et al and has not been taken into account in the study made by Sakurai and Okajima.) In this way an average thermal spectrum yield of 0.0162 is obtained in [1]. We note that this is consistent with the thermal yield measurement made by Parish (1997), who obtained the value 0.0159 ± 2.5%. The difference between the values obtained by Fort *et al* and by Sakurai and Okajima for the fast reactor spectrum yield in ^{235}U is larger, 3.6% (the values being 0.01658 ± 1.6% and 0.0160 ± 1.8%, respectively). This could be partly because of the independent evaluation of the R2 and ZONA2 measured β_{eff} values and associated uncertainties in the study by Fort *et al* and the use of an earlier interpretation of the measured values in the adjustment study by Sakurai and Okajima. (We can note that allowing for an increased systematic error associated with the measurements made in SNEAK and ZPR, by increasing the systematic uncertainty from 1% to 3%, reduces the fast spectrum adjusted values for ^{235}U, ^{238}U and ^{239}Pu by about half a percent.) The recommended value given in [1] is a weighted average of the values of Fort et al and of Sakurai and Okajima, 0.0163.

The β_{eff} measurement made in MISTRAL-2 gives confidence in JEF-2.2 calculations made for MOX fuelled thermal reactor systems. The thermal yield value for ^{239}Pu obtained by Fort *et al* is 0.00651 ± 1.7%. The thermal yield value obtained in the adjustment study of Sakurai and Okajima, 0.00638 ± 3.6%, is determined by the fast reactor systems included in the study together with an assumption on energy dependence. Their value is 2.0% lower than the value obtained by Fort *et al*. but is essentially consistent with the unadjusted JENDL-3.2 value of 0.00650, which was chosen in [1] as the recommended value. The fast reactor spectrum averaged yield values derived for ^{239}Pu from the results of the two adjustment studies, 0.00656 ± 2.6% (Fort *et al*) and 0.00642 ± 3.6% (Sakurai and Okajima) differ by 2.2%. The recommended value in [1] is the weighted average, 0.00651.

The uncertainties given in the Table for the adjusted values corresponding to the data of Fort *et al* are not the final uncertainties proposed by Fort *et al* for the spectrum averaged values. They have modified the values to take account of other contributions to the overall uncertainty and have also averaged the energy dependent uncertainties differently. Sakurai and Okajima have given a covariance matrix for their adjusted data. Rather than derive estimated uncertainties for the recommended values it is proposed here simply that an uncertainty figure be given for the values of β_{eff} calculated using these yield values. As is described in the next section it is considered that using these recommended yield values an accuracy of ± 3% (1 s.d.) will be achieved in β_{eff} calculations for the major actinides in conventional reactors (to be combined with any additional sources of uncertainty due to relative fission rate and fission rate distribution calculations and calculations of the relative importances of delayed neutrons).

It is interesting to compare with the recommendations for the three major isotopes in thermal and fast reactor spectra made by Tuttle in 1979 (based on an evaluation of the measurements of total yields). The values recommended here are 0% to 3% smaller than Tuttle's values for ^{235}U, 3% to 4% larger for ^{239}Pu and 5.6% larger for ^{238}U.

5. THE ACCURACY OF β_{eff} CALCULATIONS MADE FOR CONVENTIONAL REACTORS USING THE RECOMMENDED YIELD DATA

The target accuracy which has been proposed for β_{eff} calculations is ± 3% (1 s.d.). We examine in the following paragraphs the reasons why we consider this target to be met for conventional thermal and fast reactors fuelled with uranium or mixed uranium-plutonium. It is more clearly met for fast reactors than for thermal reactors because there are fewer measurements of β_{eff} available for validating the calculations for thermal systems.

For uranium fuelled thermal spectrum systems three measurements (or programmes of measurement in the case of the SHE programme result) have been used to validate calculations, SHE-8, (which is representative of the SHE programme), MISTRAL-1 and the TCA uranium fuelled core. Using the recommended data we estimate the discrepancies between calculation and measurement (and the standard deviations of the measurements) to be:

SHE-8 -2.2% ± 1.2% (the s.d. of the mean value derived from the programme)
MISTRAL-1 +0.6% ± 1.6%
TCA (U fuel) +3.2% ± 2.2%

The discrepancy between the yield data derived from the SHE programme and the TCA measurement needs to be understood. The discrepancy for the TCA measurement is slightly beyond the 3% target.

For MOX fuelled cores we have a direct calculation only for MISTRAL-2. Using the recommended data the discrepancy is:

MISTRAL-2 -0.5% ± 1.6%

It should be noted that there is a significant contribution from ^{241}Pu and so the measurement essentially validates the data for the particular plutonium vector (or ^{241}Pu/^{239}Pu ratio). It is reported that for the U/Pu fuelled core studied in TCA there is agreement between measurement and the JENDL-3.2 calculation. The thermal spectrum ^{239}Pu yield in JENDL-3.2 is 4.3% lower than the value recommended here. The discrepancy in the β_{eff} value will depend on the fractional contribution of ^{239}Pu, but the discrepancy could well be -3%, or more.

More measurements on thermal systems, and analyses of existing measurements, are needed to give the required degree of confidence in calculations for thermal systems.

For fast spectrum systems there are many more measurements and the measurements are more consistent. The values of β_{eff} calculated by Fort et al using JEF-2.2 yield values are within 1 s.d. of the measurement for all excepting 3 of the 19 fast spectrum measurements treated, and the assumed measurement uncertainty is less than ± 3% for most measurements. Relative to JEF-2.2 the recommended fast spectrum yields are reduced by 1.7% for ^{235}U, reduced by 1% for ^{238}U and increased by 0.8% for ^{239}Pu. There is also the trend for the benchmark measurements to give values about 2% lower than the SNEAK and ZPR series of measurements. We also recall that for R2 the measured value derived by Fort et al is about 2.6% higher than that derived by Okajima et al. We conclude that for fast spectrum systems fuelled with ^{235}U, ^{238}U and ^{239}Pu the β_{eff} value calculated using the recommended yields will have uncertainties of between ± 2% and ± 3%.

CONCLUSIONS

The energy dependence of total delayed neutron yields is believed to be small, the difference between thermal reactor and fast reactor spectrum averaged values being at most 1% or 2%. Fission product precursor summation calculations give much larger differences and the reason for this needs to be understood. The uncertainty about the possible variations through resonances is another factor which prevents a clear conclusion being reached about the relationship between thermal and fast spectrum yields. More work is needed to define the energy dependence of total yields. However, very accurate relative measurements (±1%) will be required.

It is suggested that more account should be taken of the measured delayed neutron data when evaluating fission product yields. The aspect which could perhaps be taken into account most easily is the difference between thermal and fast spectrum delayed neutron data and measurements of energy dependence of total yields and relative abundances.

For the minor actinides the uncertainties are larger and more measurements having a lower precision would be useful. For the more exotic systems which are being studied at the present time, with contributions from intermediate energies being significant in some designs, more information could be required about the energy dependence at Mev energies. For the reactor systems for which β_{eff} measurements have been made, and used as the basis for the adjustment studies summarised here, the sensitivity to these higher energies is too small for useful higher energy information to be obtained.

Accurate relative measurements of the energy dependence of total yields, and of the fractional yields used to represent time dependence, would enable the systematics of the interrelationships to be explored in more detail.

The JEF-2.2 and JENDL-3.2 total yield data give satisfactory results for the systems studied, there being no strong indication of a need to change them. The β_{eff} values calculated using ENDF/B-VI yields for the SNEAK and ZPR MOX fuelled cores are particularly low, although the values calculated for the benchmark series of cores are within about ± 3% of the measured values. The low values calculated using ENDF/B-VI for the MOX fuelled cores are considered to be a consequence of the lower yield for ^{238}U.

There is a tendency for the measurements made in the benchmark series of cores to yield lower values of β_{eff} than the measurements in the SNEAK and ZPR cores. The adjustment study made by Sakurai and Okajima, based on the benchmark series alone, has resulted in smaller yield values than the study by Fort *et al* which has included the SNEAK and ZPR measurements. However, we note that the uncertainties estimated for the SNEAK and ZPR measurements in the study by Fort *et al* are comparatively low when compared with those of the benchmark series, which are based on several independent measurements made in each core. For this reason the adoption of an average of the adjusted values based on the two studies was proposed in [1]. It is considered that using these averaged values an accuracy of ± 3% (1 s.d.) will be achieved in β_{eff} calculations for conventional thermal reactors and ± 2% to ± 3% for fast reactors fuelled with the major actinide isotopes (to be combined with any additional sources of uncertainty due to relative fission rate and fission rate distribution calculations and calculations of the relative importances of delayed neutrons, although the uncertainties arising from the use of different cross-section sets appear to be small).

Effects which have been considered in the past but which have not been discussed here include the possibility of chemical binding effects influencing delayed neutron emission and the role of (γ,f) and (γ,n) reactions associated with the delayed gamma emission.

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