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DELAYED NEUTRON DATA FOR THE MAJOR ACTINIDES

A report by the Working Party
on International Evaluation Co-operation
of the NEA Nuclear Science Committee

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NUCLEAR ENERGY AGENCY
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FOREWORD

A Working Party on International Evaluation Co-operation was established under the sponsorship of the OECD/NEA Nuclear Science Committee (NSC) to promote the exchange of information on nuclear data evaluations, validation and related topics. Its aim is also to provide a framework for co-operative activities between members of the major nuclear data evaluation projects. This includes the possible exchange of scientists in order to encourage co-operation. Requirements for experimental data resulting from this activity are compiled. The working party determines common criteria for evaluated nuclear data files with a view to assessing and improving the quality and completeness of evaluated data.

The parties to the project are: ENDF (United States), JEF/EFF (NEA Data Bank Member countries) and JENDL (Japan). Co-operation with evaluation projects of non-OECD countries, specifically the Russian BROND and Chinese CENDL projects, are organised through the Nuclear Data Section of the International Atomic Energy Agency (IAEA).

The following report has been prepared by Subgroup 6, which was set up in 1990 with the aim of reducing the discrepancies between calculated and measured values of the reactivity scale based on reactor kinetics. These discrepancies were resulting in undesirable conservatism in the design and operation of reactor control systems. A collaborative effort was initiated to reduce the uncertainties in the delayed neutron data used in these calculations. This effort included international benchmark measurements of the effective delayed neutron fraction, made on fast critical assemblies, which aimed to provide high-quality experimental information for ^{235}U, ^{238}U and ^{239}Pu. A study was also made of the representation of the time dependence of delayed neutron emission. Based on this work new recommendations have been made concerning the total delayed neutron yields for ^{235}U, ^{238}U and ^{239}Pu, and the time dependence and energy spectra for delayed neutron emission in the fission of a comprehensive set of isotopes.

The opinions expressed in this report are those of the authors only and do not necessarily represent the position of any Member country or international organisation. This report is published on the responsibility of the Secretary-General of the OECD.

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***Additional subgroup documents available on the enclosed CD-ROM*:**

Document No. 1. Recommended Values of the Delayed Neutron Yield for Uranium-235, Uranium-238 and Plutonium-239
E. Fort, V. Zammit-Averlant, M. Salvatores and J-F. Lebrat (CEA, Cadarache).

Document No. 2. A Summary of Measured Delayed Neutron Group Parameters
G.D. Spriggs and J.M. Campbell (LANL), LA-UR-98-918

Document No. 3. An Eight-Group Delayed Neutron Model Based on a Consistent Set of Half-lives
G.D. Spriggs (LANL), J.M. Campbell (LANL) and V.M. Piksaikin (IPPE), LA-UR-98-1619

Document No. 4. Delayed Neutron Spectral Data for Hansen-Roach Energy Group Structure
Joann M. Campbell and Gregory D. Spriggs (LANL), LA-UR-99-2988

Document No. 5. Progress Report on Delayed Neutron Measurement Activities at IPPE Obninsk
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SUMMARY

Subgroup 6 was set up in 1990 with the task of co-ordinating activities aimed at reducing the discrepancies, which then existed, between calculated and measured nuclear reactor reactivity scales based on reactor kinetics. The main aim has been to reduce the uncertainties in the delayed neutron data for the major actinides, ^{235}U, ^{238}U and ^{239}Pu. In this final report of the subgroup recommended delayed neutron data are proposed for these isotopes and the state of the art in the field of delayed neutron data is reviewed. Recommended data for the time dependence of delayed neutron emission and for the associated energy spectra for fission in 20 isotopes are also proposed.

The report is accompanied by a CD-ROM which contains a number of documents providing more detail about the derivation of the recommended data. In addition, papers describing the measurements made at IPPE Obninsk concerning total yields and time dependence, as well as associated studies of semi-empirical models, are also available on the CD-ROM.

The report presents an overview of the state of the art. Short descriptions are given of the different activities, together with bibliographic references. Some recent results are also reported. The report is organised in four sections. The first section summarises general analyses of the available delayed neutron data. The remaining three sections summarise activities carried out to measure, evaluate and validate delayed neutron data at the following three levels:

- the level of the individual precursors (or microscopic data) and their utilisation in summation calculations;
- the level of the aggregate precursor (or macroscopic data);
- the level of the in-pile integral measurements and related macroscopic data validation studies.

The papers by Fort, *et al*. [131] (document No. 1 on the CD-ROM) and by Sakurai and Okajima [130] describe the derivation of recommended total delayed neutron yields for the major actinides, ^{235}U, ^{238}U and ^{239}Pu based on an analysis of beta-effective measurements made on critical assembly facilities. These include the series of international benchmark measurements made by teams from several different countries, using different techniques, on fast critical assemblies built on the facilities MASURCA at Cadarache, France, and FCA at JAERI, Japan. These benchmark measurements are described in the paper by Okajima, *et al*. [90]. The recommended total yield data for ^{235}U, ^{238}U and ^{239}Pu are summarised in Appendix 2.

An important activity of the subgroup has been the production of recommended data to represent the time dependence of delayed neutron emission. The recommended approach is to use an eight time-group representation, with the three longest-lived groups having the half-lives of the three dominant long-lived precursors, ^{87}Br, ^{137}I and ^{88}Br. The same set of eight half-lives is used to represent the time dependence for all fissioning isotopes. The studies upon which the evaluations are based are described in two documents presented on the CD-ROM, documents No. 2 and 3. The procedure used to decide on the form of the recommended time dependence, and the methods used to derive the relative abundances in this form, are described in LA-UR-98-1619 (document No. 3). The recommended data and the associated energy spectra for the eight-group data are given in LA-UR-99-4000, along with a description of the methods used to derive the spectra. The energy group structure used to represent the spectra is the Hansen and Roach 16-group structure. The recommended eight-group relative abundances and energy spectra are given in Appendix 3.

One of the most active laboratories making measurements at the macroscopic level, and developing theoretical models, continues to be IPPE Obninsk. The CD-ROM contains a progress report from this laboratory (document No. 5) along with three papers describing recent work.

REVIEW OF THE STATE OF THE ART

A. D’Angelo, J. Rowlands

1. Introduction

Subgroup 6 was set up in April 1990. Its task was outlined as follows:

> “Current calculation-to-experiment discrepancies (up to 10%) on integral measurements of the delayed neutron effective fraction (β_{eff}) result in undesirable conservatism in design and operation of reactor control systems. Delayed neutron data uncertainties, which are significant in β_{eff} calculations, may be summarised as follows: absolute yields ±4 to 5%; group parameters ±3 to 15%; delayed spectra ±10 to 20%. A collaborative effort to improve these data is recommended. The resultant data could also be tested with the new integral experiment measurements on β_{eff}, which are being proposed as international benchmarks and which are expected to provide high quality experimental information relative to ^{239}Pu, ^{235}U and ^{238}U.”

Many tasks to improve delayed neutron (DN) data have been planned and most of them successfully carried out. Important results have been obtained, allowing significant reductions to be made with regard to the uncertainty on the reactor reactivity scale and to improve its time dependence. Among these activities, the following may be briefly summarised here:

- the measurement and evaluation campaigns to improve databases of independent and cumulative fission product yields, half-lives and DN emission probabilities;

- the use of these improved databases in summation calculations to obtain macroscopic data;

- the measurement of the ^{235}U, ^{233}U, ^{239}Pu and ^{237}Np DN fraction and group constants for fission induced by cold neutrons at the IBR-2 pulsed reactor of the Frank Laboratory of Neutron Physics at Dubna (Russia);

- the measurements of the ^{235}U and ^{237}Np absolute DN yield and group constants for fission induced by fast neutrons (range 0.5-5MeV) using the electrostatic accelerators at IPPE, Obninsk (Russia);

- the recent measurement at IPPE, Obninsk, of ^{239}Pu group constants in the range from thermal to 5 MeV;

- the measurement of the ^{235}U, ^{237}Np, ^{241}Am and ^{243}Am absolute DN yield and group constants at the Nuclear Science Centre TRIGA reactor of Texas A&M University (USA);

- the measurement of the ^{235}U and ^{237}Np absolute delayed neutron yield at the GODIVA-4 fast facility at Los Alamos (USA);

- the measurement of the ^{235}U and ^{238}U absolute delayed neutron yield, and group constants using the Dynamitron accelerator facility at Birmingham University (UK);

- two experimental campaigns, in the MASURCA fast critical facility at Cadarache (France) and in the FCA fast critical facility at Tokai-Mura (Japan), to provide international benchmark β_{eff} measurements;

- the data validation studies at Cadarache (France) and at JAERI, Japan, to recommend DN total yields for the major fissile isotopes;

- the improvement of empirical correlation models at IPPE Obninsk to estimate both total DN yields and precursor average lifetimes;

- the definition of a new eight-group structure to represent the time dependence of DN emission, having a better physical basis and a more convenient form than the present widely used six groups, work done at Los Alamos in co-operation with IPPE, Obninsk;

- the evaluation of recommended relative abundances in the new eight-group structure for 20 fissionable isotopes (the above-mentioned co-operation between Los Alamos and IPPE, Obninsk);

- the derivation of aggregate DN spectra in the six- and eight-group structures at Los Alamos using the most recent data for cumulative fission yields, emission probabilities and precursor spectra.

Many of these studies are described in papers to be published in a special issue of *Progress in Nuclear Energy*. Moreover, a special issue of the journal has already presented the results of the International Benchmark Experiment of Effective Delayed Neutron Fraction in the Fast Critical Facility (FCA), JAERI (Okajima, *et al.*) [134].

This report aims to give a picture of the state of the art of all the activities on delayed neutron data carried out during the last ten years. It is organised in four parts. The first section briefly summarises general analyses of the available DN data. The other three sections summarise activities carried out at the classical three levels of DN data:

1. measurements and evaluations of individual precursor (or microscopic) data and the use of these data in summation calculations;

2. aggregate precursor (or macroscopic) data measurements and evaluations;

3. in-pile integral measurements, calculational result sensitivity analyses and related macroscopic data validations.

The recommendations for reactor physics applications are then briefly summarised.

This is followed by an extensive bibliography; however, a complete bibliography on the subject cannot be produced because some of the work has been carried out specifically for a particular Nuclear Data Library project and consequently has not received a wide distribution.

2. Analyses of the status of the available delayed neutron data

Because of the general interest in accurate predictions of reactor kinetics, some important reviews of the status of the data, and of the requirements for improvements in the accuracy of the data, have been carried out in the past ten years. These include reviews by Blachot, *et al.* [1], Das [2], Weaver [3], Parish, *et al.* [4], Rowlands [5] and Nakagawa [6]. These studies investigate the overall status of the data and include some uncertainty analyses and recommendations. More particularly:

- In 1990, when the subgroup was first established, Blachot, *et al*. [1] reviewed the status of the data for the major isotopes. In particular, the paper stressed the need to improve the accuracy of total DN yields to reduce the uncertainties on calculations of the reactivity scale for fast reactors.

- The papers by Das [2] give a comprehensive and accurate assessment of the state of the art of DN data and, in particular, a detailed analysis of delayed neutron energy spectra.

- The lecture on delayed neutrons by Weaver [3] provides a comprehensive and didactic introduction to the subject, and also contains DN yield data obtained by R.W. Mills and D. Hale using the summation technique and a comparison with measured values.

- The contribution by Parish [4] concerning the status of the six-group constants used to represent time dependence has been particularly important. In his careful analysis, he identified the main sources of the discrepancies previously pointed out by some reactor physicists by comparing results obtained using various data files [2,7-12].

- In January 1999, at a Specialists Meeting on Delayed Neutron Nuclear Data held at JAERI, Japan, the DN data for ^{235}U, ^{238}U and ^{239}Pu adopted in the JENDL-3.2, ENDF/B-VI.5 and JEFF-2.2 libraries were reviewed by Nakagawa [6].

3. Microscopic data measurements, modelling, evaluations and utilisation in summation calculations

Measurement activities and important theoretical modelling studies, evaluations and utilisation of the data in summation calculations have been carried out for data at the individual precursor level, both in the framework of the activities of the subgroup and independently.

3.1 Measurements at the Neutron Research Laboratory, Studsvik

In the early 1990s, when G. Rudstam of the Studsvik Neutron Research Laboratory of Uppsala University was (until his retirement) co-ordinator of the subgroup, a very large amount of DN data was measured and evaluated by his group. In particular there was the work related to the P_n values and half-lives of precursors [13,14] as well as independent and cumulative yields of fission products [15].

This rich tradition of microscopic data measurements using the ISOL facilities of OSIRIS at the Studsvik Laboratory continues. These facilities were mainly designed to study the nuclear structure and decay properties of radioactive neutron-rich nuclei emitted or extracted from a fission target [16]. The recent work on fast neutron-induced fission of ^{233}U [17,18] is an example of the continuing use of the facility to measure independent and cumulative fission product yields from thermal or fast neutron-induced fission of uranium and thorium nuclides. (This nuclide limitation is due to the risk of possible structural instabilities of the target, which is heated up to 2 200°C during the measurement.) The measurement method covers a wide mass range (the whole double-humped mass curve). The resulting precision depends on the accuracy of the information on:

- the ionisation process of each element and associated time scale and efficiency;

- the information required to derive the correction factor in the production due to the radioactive precursor in the β decay chain;

- the γ branching ratios required for the analysis of the measured nuclide.

3.2 Measurements at ILL Grenoble

Another major contribution to fission data measurement results from the use of the prolific source of thermal neutrons provided by the High Flux Reactor at ILL Grenoble (France) and the development of physical methods based upon in-flight techniques [19] to investigate the fission fragment properties [20,21]. The LOHENGRIN facility is now providing extensive and high precision data on the mass, charge, energy and velocity of fission fragments from a wide range of target nuclei, including some minor actinides, such as ^{245}Cm [22-24]. Measurements of P_n values using the LOHENGRIN facility are also planned starting with ^{235}U and ^{239}Pu targets [25]. Moreover, there are plans to use the LOHENGRIN mass spectrometer to investigate DN emission from fragments produced in the fission of heavy nuclei such as ^{241}Pu, ^{245}Cm and ^{249}Cf [26].

3.3 Measurements at GSI Darmstadt

Fission experiments with secondary beams [27,28] have been carried out at GSI Darmstadt (Germany) using the “fission in inverse kinematics” method that provides a powerful means to systematically investigate the ratio of symmetric to asymmetric fission versus the mass of the fissile system and to test the concept of independent fission modes (or channels). Instead of projecting a neutron or another particle onto the fissile nucleus, the fissile nucleus is itself projected with a relativistic energy through a target (usually lead) and when excited in this way it undergoes fission in flight (so-called electromagnetic-induced fission). The main advantage [21,29,30] is that the kinetic energy of the fissioning nucleus adds to the kinetic energy of the fission fragments. This leads to a better resolution of the fission fragment's nuclear charge, thus allowing the measurement of Z for both light and heavy fragments. Another advantage lies in the fact that the fissile nucleus is produced directly before it undergoes fission: having a long lifetime is not a prerequisite. In principle, any bound isotope can be studied in this way. As stressed by Schmidt, *et al*. [28], the nuclear charge and mass number of the secondary projectiles can be freely selected by tuning the fragment separator within the limits given by the primary-beam intensity and the fragmentation cross-sections.

3.4 Measurements at the University of Lowell Research Reactor

Independent fission-product yield measurements at the University of Massachusetts Lowell research reactor have been interpreted and the results have been compared to the ENDF/B-VI values [31]. The yields measured were of short-lived fission products following ^{238}U fast fission. They have been measured with a 10% uncertainty and only 28% of the nuclides had previously measured values given in ENDF.

3.5 Empirical models for the estimation of fission fragment yields

The latest version of the models developed by Wahl [32] can predict:

- the fission product mass distribution from fission of nuclei with atomic numbers Z_F = 90-99 and excitation energies $E^* \leq 20$ MeV;

- the fission-product nuclear charge distribution from fission of nuclei with atomic numbers Z_F = 92-98 and excitation energies $E^* \leq 20$ MeV.

The Z_p and A'_p empirical models are currently being improved by a new IAEA Co-ordinated Research Project (CRP) on fission of minor actinides of interest for transmutation purposes induced by neutrons having energies up to 150 MeV.

3.6 Evaluations of microscopic data

Complete and very important programmes of measurement, evaluation, compilation and review of independent and cumulative fission product yields have been carried out for the ENDF/B-VI, JENDL and JEF-2 files by England and Rider [33], Denschlag [34] and Mills [35] and intercompared by an IAEA Co-ordinated Research Project [30].

Evaluations to produce databases of DN emission probabilities have been carried out [36, 37]. In particular, the Hale, *et al.* [37] database was recently generated using Rudstam's evaluation of experimentally determined P_n values (98 nuclides) and calculated P_n values based on the Kratz-Herrmann formula for the (174) remaining nuclides. More recently, half-lives and neutron emission probabilities have been measured by Pfeiffer, Kratz and Moeller [132] and comparisons made with theory.

Some theoretical P_n values derived by Klapdor-Kleingrothaus were also incorporated in the JEF-2 evaluation [36].

3.7 Developments of theoretical methods

Theoretical studies in Japan have produced the "gross" theory [38] and data obtained using this theory have been used to supplement the measured data in summation calculations [39]. More recently, the theoretical studies in Japan have resulted in the development of the so-called "semi-gross" theory [40]. This latest theoretical method for estimating β-decay properties, such as half-lives and DN emission probabilities, in the region far from the β stability line, has been obtained by refining the conventional gross theory to take into account some shell effects of the parent nucleus. However, the P_n values obtained using the semi-gross theory are lower than the experimental values in many cases. In order to get more reasonable P_n values, a modification has been made to the theory, introducing an energy broadening with a width which depends on the excitation energy [41].

In Russia, Bogomolova, *et al*. [42] have used a thermodynamical approach to subatomic phenomena to produce a library of actinide fission-product yields, (ASIND-MEPhI).

Many empirical nuclear parameter correlations with respect to the 2Z-N value of the nucleus have been analysed. The correlation method has been used either to estimate chain and independent fission-product yields [43] or to directly estimate unmeasured total DN yields (see also Section 4.7).

3.8 Summation calculations and assessments of measurement requirements

Several calculations of total DN yields and of the group constants representing time dependence have been carried out using different evaluations [3,44-48].

An interesting microscopic data intercomparison [49], based on a simple method [50], has identified the most important discrepancies (in general in the P_n values) between different microscopic data libraries. The results of this work, together with results from uncertainty analyses [51], have been used to decide priorities for microscopic data measurements. These studies confirm that DN data obtained by the summation method are still affected by uncertainties much higher than those obtained by means of macroscopic data evaluations. In particular, the need for more precise P_n measurements has been underlined, to reduce summation calculation uncertainties.

3.9 Derivation of the group constants used to represent time dependence by means of summation calculations

The six-group constants obtained using the summation technique with ENDF/B-VI microscopic data have recently been improved at Los Alamos. The older calculations were made using the CINDER-10 code with pre-ENDF/B-VI fission-product yields. The calculation tracked the delayed neutron production to 300 seconds following the fission event. Moreover, in the older six-group fits, all 12 parameters of the six-group expression were free to vary in the search for a minimum χ^2 value. More recently, Wilson and England [52] have used the CINDER'90 code to model the 60 fission systems in the ENDF/B-VI yield library [33] using the half-lives and neutron emission probabilities given by Pfeiffer, Kratz and Moeller [132].

3.10 Delayed neutron spectra

The aggregate delayed neutron spectra previously calculated at the Los Alamos National Laboratory from precursor data [53] have been validated. Calculated spectra have been compared with delay interval spectra and equilibrium spectra measured at the University of Lowell for thermal fission in ^{235}U and ^{239}Pu and fast fission of ^{238}U [54]. More recently, as a part of the work to produce recommended data, the DN spectrum for each fissionable isotope was recalculated by Campbell and Spriggs [55] using up-to-date data for cumulative fission yields, emission probabilities and precursor spectral data. In particular, both for Keepin's classical six-group structure and for the new eight-group structure, new sets of DN spectra that match the decay constants of these sets have been produced in a fine energy group description (10 keV energy bins). Finally, these data have been collapsed into the energy intervals of one of the most commonly used sets of nuclear cross-sections: the 16-group Hansen-Roach set. This work is described more fully in the paper LA-UR-99-4000. The eight time-group spectral data (in 16 energy groups) are given, together with the eight-group relative abundances, in Appendix 3.

New measurements of DN spectra from selected precursors have been carried out at the Idaho National Engineering Laboratory using H_2 and CH_4 gas-filled proton-recoil proportional counters [66]. Thanks to the proton-recoil detector being insensitive to thermal and epithermal neutrons, in comparison with the ^{3}He ionisation chambers used in many previous measurements, these measurements can help to solve some residual low-energy discrepancies between different DN spectrum measurements that have been studied by Das [2].

3.11 The energy dependence of total DN yields and variations through the resonance region

The total DN yield data for ^{235}U and ^{239}Pu in the JEF-2.2 library have been evaluated by Fort, *et al.* [57] using Lendel's semi-empirical model [58] to calculate the energy dependence. This energy dependence is calculated as a function of the prompt neutron yield, ν_p (and other characteristics of the fissioning nucleus). The variations of ν_p through the resonance ranges result in corresponding variations in the calculated total DN yields of the two isotopes.

The possibility of fluctuations in DN yields in the ^{235}U resonance region has also been investigated by Ohsawa and Oyama [59] analysing fluctuations in the fission fragment mass distribution in terms of the multi-modal fission model [60]. The variations are found to be small, about 1%, in this study, and are correlated differently with the variations in ν_p.

4. Macroscopic data measurements and evaluations

Reactor β_{eff} and time-dependent reactivity scale calculations are mainly sensitive to the total DN yield and to the group constants representing time dependence, respectively. Whenever available, total yield values and group constants evaluated at the macroscopic level are generally used for reactor calculations. To obtain a further improvement in the precision of the reactor reactivity scale further investigations at this macroscopic or aggregate precursor level were needed. For this reason, measurement campaigns to improve the precision of data at this level were promoted and monitored. The subgroup also started to investigate more deeply the dependence on incident neutron energy.

Work still in progress and future macroscopic data activities will be mainly focused on:

- data for the minor actinides and the Th fuel cycle of interest for new concepts of nuclear reactors, such as actinide burners;

- the problem of the dependence on the incident neutron energy.

Among the main data activities at the macroscopic level, the studies outlined in the following sections are particularly to be mentioned.

4.1 Measurements and analyses carried out at IPPE Obninsk

The measurement of the ^{235}U, ^{238}U and ^{237}Np absolute DN yield and of the ^{235}U and ^{237}Np group constants for fissions induced by fast neutrons (range 0.5-5 MeV for ^{235}U and ^{237}Np and 1-5 MeV for ^{238}U) has been carried out at the electrostatic accelerators at IPPE, Obninsk, by Piksaikin, *et al*, [61,62]. The experimental method was based on periodic irradiation of fissionable samples by neutrons from suitable nuclear reactions at the accelerator target. Different irradiation times were used to emphasise the importance of different DN groups. A pneumatic transfer system was used for the transportation of a sample from the irradiation position to the neutron detector. The minimum sample delivery time was about 150 ms. The neutron detector was an assembly of 30 boron counters distributed in polyethylene along three concentric circles. The fission rate in the fissile samples was determined by using two parallel fission chambers installed in front of and behind the sample. Monte Carlo correction factors were used to evaluate multiple scattering effects in structural materials.

These measurements allowed important experimental information to be obtained on the energy dependence of:

- ^{237}Np total delayed neutron yield and group constants;

- ^{235}U and ^{238}U total delayed neutron yield;

- ^{237}Np relative delayed neutron yields related to individual precursors.

Measurements of the total yields of ^{235}U and ^{237}Np

The following absolute total DN yield results are those for an incident neutron energy of about 1.15 MeV (1.165MeV for ^{235}U and 1.154 MeV for ^{237}Np):

$$\upsilon_d(^{235}\mathrm{U}) = 0.0171\pm4.8\% \text{ and } \upsilon_d(^{237}\mathrm{Np}) = 0.0114\pm4.7\%$$

The group constant results presented in Table A1.1 (in Appendix 1) also relate to the same incident neutron energies. (The results for ^{237}Np total have been changed from those published in Ref. [61], because it was found that incorrect data had been used in the processing of the fission chamber data.) To obtain information on the incident neutron energy dependence, a second absolute ^{237}Np DN yield measurement was made at the incident neutron energy of 3.868 MeV:

$$\upsilon_d(^{237}\mathrm{Np}) = 0.0088\pm5.7\%$$

Moreover, five supplementary relative measurements were performed for both ^{237}Np and ^{235}U. The results for the absolute measurements are presented in Tables 1 and 2 and the relative measurements of incident neutron energy dependence in Tables 3 and 4 and in Figure 1. In Table 3 the relative data for ^{235}U have been normalised to the interpolated value at E_n = 0.742 MeV between Tuttle's 1979 recommended values for thermal and fast neutrons [63] and, in Table 4, the relative ^{237}Np data have been normalised to the absolute IPPE measurement at 1.154 MeV

Table 1. Total delayed neutron yield for fast neutron-induced fission of ^{235}U at 1.165 MeV

IPPE work	Keepin	Besant	Tuttle, 1979
0.01709±0.00082	0.0164±0.0005	0.0164±0.0006	0.01673±0.00036

Table 2. Total delayed neutron yield for fast neutron-induced fission of ^{237}Np

IPPE work	Benedetti	Gudkov	ENDF/B-VI
E_n = 1.154 MeV 0.01141±0.00054	Fast 0.0122±0.0003	Fast 0.01180±0.0013	Fast 0.01068±0.00098
E_n = 3.868 MeV 0.00877±0.00050			

Table 3 Total DN yield from fission of ^{235}U as a function of incident neutron energy

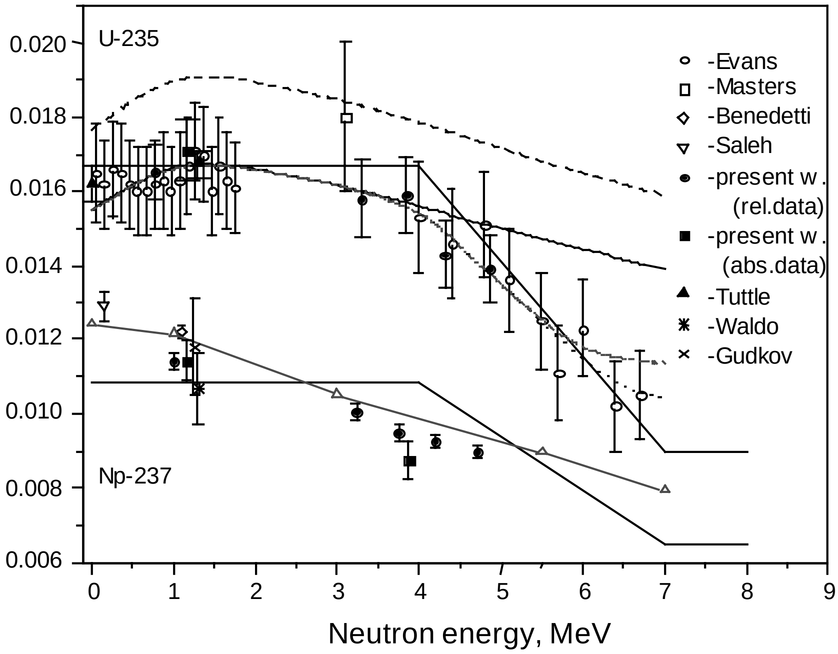
Neutron energy, E_n, MeV	Total DN yield, n/fission	Uncertainties
0.742	0.0165	0.0008
3.274	0.0158	0.0010
3.805	0.0159	0.0010
4.269	0.0143	0.0009
4.805	0.0139	0.0009

Table 4. Total DN yield from fission of ^{237}Np as a function of incident neutron energy

Neutron energy, E_n, MeV	Total DN yield, n/fission	Uncertainties
1.008	0.01141	0.00025
3.231	0.01006	0.00022
3.745	0.00948	0.00019
4.196	0.00926	0.00019
4.719	0.00897	0.00018

In Figure 1, the lines which are constant to 4 MeV and then show a linear decrease to 7 MeV followed by a constant value are the ENDF/B-VI evaluations. For ^{237}Np the open triangles connected by a solid line indicate the IPPE evaluation. For ^{235}U the dashed line indicates a calculation based on independent yield (IY) data from the report JAERI-M-89-204 [135]; the solid line indicates calculated results obtained using IY data including the available experimental data; the dash-dotted line indicates the same as the solid line but the energy dependence of ν-prompt for the light fission fragment was taken into account; the dotted line indicates the same as the dash-dotted one, but second chance fission was taken into account.

Figure 1. Total DN yields for neutron-induced fission of ^{235}U and ^{237}Np



Energy dependence of the delayed neutron yields from individual precursors in ^{237}Np fission

In order to obtain information on the ^{237}Np relative delayed neutron yields from individual precursors, a new iterative least-squares method has been used by Piksaikin, *et al*., (CD-ROM Document No. 5, Part 2) to analyse the results. In the first step the values of the relative DN yields of 17 precursors were estimated using the following half-life values (s) from T.R. England, *et al.* [136]: 55.69 (^{87}Br), 24.5 (^{137}I), 16.3 (^{88}Br), 6.46 (^{138}I), 5.93 (^{93}Rb), 4.38 (^{89}Br), 2.76 (^{94}Rb), 2.3 (^{139}I), 2.08 (^{85}As), 2.0 (^{98m}Y), 1.289 (^{93}Kr), 1.002 (^{144}Cs), 0.86 (^{140}I), 0.542 (^{91}Br), 0.384 (^{95}Rb), 0.203 (^{96}Rb), 0.17 (^{97}Rb). It turns out that there is a strong correlation between the initial parameter values and the final results for the relative DN yields for the precursors with the following half-lives: 6.46 and 5.93 s; 2.3, 2.08 and 2.0 s; 1.002 and 0.86 s; 0.203 and 0.17 s. To solve this problem the above precursors were combined in four groups with the effective values of half-life equal to 6.37, 2.09, 0.942, 0.195 s. The values of the effective half-lives for these groups were obtained by an averaging procedure with the values of the relative DN yield [64] as a weight. The precursor half-lives presented in Table 5 were obtained for eight individual precursors and four groups of combined precursors.

Table 5. Energy dependence of relative delayed neutron yields related to individual precursors for neutron-induced fission of ^{237}Np

		Neutron energy, MeV				
Precursor	**T, s (half-life)**	0.586 (±0.078)*	1.008 (±0.099)	3.745 (±0.144)	4.196 (±0.169)	4.719 (±0.205)
		Rel. DN yield				
^{87}Br	55.69	0.030 ±0.001	0.031 ±0.001	0.035 ±0.001	0.040 ±0.001	0.037 ±0.001
^{137}I	24.5	0.185 ±0.006	0.176 ±0.005	0.153 ±0.005	0.126 ±0.004	0.141 ±0.005
^{88}Br	16.3	0.105 ±0.005	0.101 ±0.005	0.085 ±0.004	0.112 ±0.005	0.088 ±0.005
^{138}I, ^{93}Rb	6.37	0.075 ±0.004	0.079 ±0.003	0.083 ±0.003	0.070 ±0.003	0.083 ±0.003
^{89}Br	4.38	0.090 ±0.007	0.092 ±0.007	0.094 ±0.007	0.095 ±0.007	0.098 ±0.007
^{94}Rb	2.76	0.129 ±0.012	0.129 ±0.012	0.130 ±0.012	0.140 ±0.013	0.136 ±0.012
^{139}I, ^{85}As, ^{98m}Y	2.09	0.257 ±0.012	0.257 ±0.011	0.261 ±0.011	0.254 ±0.011	0.259 ±0.011
^{93}Kr	1.289	0.0044 ±0.0008	0.0046 ±0.0008	0.0052 ±0.0009	0.0059 ±0.0011	0.0054 ±0.0010
^{144}Cs, ^{140}I	0.942	0.012 ±0.002	0.013 ±0.002	0.015 ±0.003	0.017 ±0.003	0.015 ±0.003
^{91}Br	0.542	0.018 ±0.003	0.019 ±0.004	0.021 ±0.004	0.024 ±0.005	0.022 ±0.004
^{95}Rb	0.384	0.073 ±0.017	0.077 ±0.017	0.091 ±0.020	0.088 ±0.020	0.088 ±0.020
^{96}Rb, ^{97}Rb	0.195	0.022 ±0.004	0.023 ±0.004	0.026 ±0.005	0.029 ±0.005	0.027 ±0.005

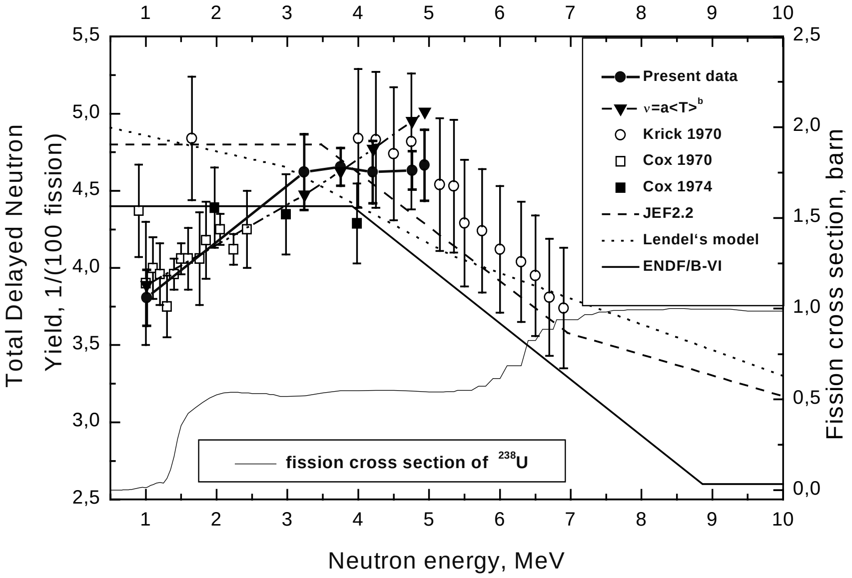
* Values in brackets are standard deviations of the incident neutron energy.

These recent IPPE experimental results can be particularly useful in comparisons with results obtained using the summation technique.

Energy dependence of the total delayed neutron yield in fission of ^{238}U

Measurements have recently been made at IPPE of the energy dependence of the total yield in fission of ^{238}U in the energy range 1-5 MeV. The results are presented in Figure 2, where they are compared with earlier measurements of the energy dependence (see document No. 5 on the CD-ROM). In the range 3 to 5 MeV the yield is approximately constant but the value at 1 MeV is markedly lower, suggesting that the yield increases significantly with an increase in energy below about 3 MeV. The measurements of Krick [127] (open circles) and Cox [128] (closed squares) are more consistent with the yield being constant between about 1.5 and 5 MeV. The earlier measurements of Cox and Whiting [129] (open squares) suggest a possible increase with increasing energy. Also shown in the figure are the values obtained on the basis of a systematics method developed at IPPE (see Section 4.6). This systematics is based on a correlation of the total yield with the mean half-life of the delayed neutrons. The values are shown by solid triangles connected by a dash-dotted line and it will be seen that the values show the same trend with energy as the IPPE measurements below about 3 MeV. For comparison, in this figure the following data are shown: solid line – ENDF/B-VI data; dashed line – the JENDL-3.2 and JEF-2.2 data; dotted line – data obtained on the basis of Lendel's model [58]. The ENDF/B-VI values are constant up to 4 MeV and then decrease with the slope of the Krick measurements. The JENDL-3.2 values (also adopted in JEF-2.2) are constant up to 3.5 MeV and then decrease with a similar slope (see Section 4.8).

Figure 2. Energy dependence of the total delayed neutron yield of ^{238}U measured at IPPE and comparison with earlier measurements and data in nuclear data libraries



The measured data below 3 MeV are very sparse but if the energy variation in this range is as indicated in the IPPE work the effect would be of importance in reactor calculations. There is a need for more detailed measurements and for theoretical studies to clarify the energy dependence.xxx

4.2 Measurements made at the Frank Laboratory of Neutron Physics, Dubna

The measurement of the ^{235}U, ^{233}U, ^{237}Np and ^{239}Pu DN fraction and group constants for fission induced by cold neutrons has been carried out at the IBR-2 pulsed reactor of the Frank Laboratory of Neutron Physics at Dubna [65]. The experimental method was based on periodic irradiation of samples. The facility consisted of a bent mirror cold-neutron guide, a slow neutron chopper and a neutron detector around the sample. The rotation of the chopper was synchronised with neutron pulses of the IBR-2 reactor and the time-of-flight method was used to determine the energy of the neutrons inducing the fissions (cold neutrons). After calibrating the ratio between the detector efficiency for prompt and delayed neutrons to obtain for ^{235}U the expected result (β of $^{235}\text{U} = 0.00680\pm2.9\%$), the following results were obtained from the experiments:

$$\beta \text{ of } ^{233}\text{U} = 0.00260\pm4\%, \ \beta \text{ of } ^{237}\text{Np} = 0.0041\pm15\%, \ \beta \text{ of } ^{239}\text{Pu} = 0.00238\pm5\%$$

where β is the ratio $\upsilon_d/(\upsilon_p + \upsilon_d)$ between the DN yield and the total yield per fission. These results can be easily interpreted as DN yields by using ^{233}U, ^{237}Np and ^{239}Pu υ_p data. Using the values of 2.4884±0.16%, 2.5218±2.% 2.876±0.18% respectively [35], these Dubna results correspond to:

$$\upsilon_d(^{233}\text{U}) = 0.00649\pm4\%, \ \upsilon_d(^{237}\text{Np}) = 0.0104\pm15\%, \ \upsilon_d(^{239}\text{Pu}) = 0.00686\pm5\%$$

As for the results on the time dependence, in both the ^{235}U and the ^{239}Pu cases the best agreement was obtained with activities calculated using the group constants recommended by Tuttle [66], *i.e.* the values evaluated by Keepin [67] for fast systems.

4.3 Measurements made at Texas A&M University

The measurement of the ^{235}U, ^{237}Np, ^{241}Am and ^{243}Am absolute delayed neutron yields and group constants has been carried out at the Nuclear Science Center TRIGA reactor of (TAMU) Texas A&M University [68-70]. Samples containing the actinide isotope were placed inside polyethylene vials and transferred to and from the irradiation position (9×10^{12} n/cm^2 s) by a fast pneumatic transfer system (transit time of about 0.5 s). Delayed neutrons were detected using an array of proportional BF$_3$ counters embedded in a polyethylene cylinder, designed using a Monte Carlo method and monitored by a computer that had a built-in 8 192-channel multi-scaler. Different irradiation times (180, 60, 20 and 5 s) were used to emphasise the importance of different DN groups: the corresponding counting time increments per channel were increased or decreased to maintain a nominal 10 000 counts per time step. The values of the sample fission rates were obtained by measuring the activity of ^{140}Ba, ^{140}La, ^{103}Ru, ^{131}I and ^{99}Mo fission products (and other fission products to obtain confirmatory information). The gamma-ray spectroscopy was performed using a high-purity germanium detector. ^{241}Am and ^{243}Am samples were placed inside a lead container to avoid dead-time problems induced by gamma rays associated with ^{241}Am and ^{243}Am decay (specific efficiency calibrations were performed in these cases by placing a ^{152}Eu calibration source in the same lead container).

Measurements were performed using two different neutron energy spectra. The results reported by Saleh, *et al.* [69] were obtained in a pneumatic receiver at a first irradiation location (called D-2). Practically, the Saleh, *et al.* [69] measurements were made by means of sample irradiations in a neutron flux spectrum more thermalised than the spectrum of the Charlton, *et al.* [70] measurements (made at the irradiation location called D-3). In particular, over 95% of the ^{235}U fissions in a sample irradiated at D-2 were induced by neutrons with energies below 10 eV. For ^{241}Am, ^{243}Am and ^{237}Np, the fraction of fissions at the D-2 location induced by neutrons with energies below 10 eV were 82%, 16% and 3% respectively [68]. The results reported by Saleh, *et al.* [69] for the total yield measurements at the D-2 location are: $\upsilon_d(^{235}\text{U}) = 0.0159\pm2.5\%$, $\upsilon_d(^{237}\text{Np}) = 0.0129\pm3.1\%$, $\upsilon_d(^{241}\text{Am}) = 0.0049\pm4.1\%$ and $\upsilon_d(^{243}\text{Am}) = 0.0084\pm4.8\%$. The corresponding group constant results are presented in Table A1.2 in Appendix 1.

The results reported by Charlton, *et al.* [70] were obtained in the fast flux pneumatic receiver at D-3. In particular, the neutron flux at energies below 10 eV is essentially decreased to zero inside the D-3 location and the fractions of the fissions below a neutron energy of 100 keV for ^{235}U, ^{237}Np, and ^{243}Am were 0.41, 0.002 and 0.003, respectively [68]. The results reported by Charlton, *et al.* [70] for the total DN yield measurements at the D-3 location are: $\upsilon_d(^{235}\text{U}) = 0.0167\pm4.8\%$, $\upsilon_d(^{237}\text{Np}) = 0.0114\pm6.1\%$ and $\upsilon_d(^{243}\text{Am}) = 0.0086\pm5.8\%$. The corresponding group constant results are presented in Table A1.3 in Appendix 1.

Recently, Texas A&M University's results reported above for the D-3 fast flux pneumatic receiver were extended to the shortest-lived group by using new experimental results. These latest results were obtained by operating the NSCR TRIGA reactor in pulsed mode [71,72] to accentuate the shorter-lived DN groups. Practically, samples of ^{237}Np and ^{243}Am were irradiated at 300 W for approximately 10 seconds, then the reactor was pulsed by adding

$1.50 reactivity. The pulse lasts for approximately 60 milliseconds. The sample was removed and transferred to the BF_3 counters at the peak of the pulse. Results are given in a seven-group structure. The pulsing technique was unable to produce enough counts to allow for accurate measurement of the Group 1 and 2a longest-lived group values. Thus, the results determined previously (Charlton, *et al.*,) [70] for Group 1 were used to produce a complete "seven-group" set. The preliminary results are presented in Table A1.4 in Appendix 1.

4.4 Measurements performed at the GODIVA facility at Los Alamos

Measurements of the ^{235}U and ^{237}Np absolute delayed neutron yields were performed at the GODIVA-4 fast facility at Los Alamos [73]. The bare GODIVA assembly provided an incident neutron source having a mean energy of about 1.3 MeV. Different sample irradiations, "instantaneous" and "infinite", were used to emphasise the importance of different DN groups. Samples containing the actinide isotope were placed in polycarbon capsules and transferred from the irradiation position ($\approx 10^{10}$ fissions) to a well-shielded counting position (distance 4.52 m) by a very fast pneumatic transfer system (transit time of about 0.110 s). The neutron detection system consisted of 20 ^{3}He tubes embedded in a cylindrical configuration inside polyethylene. The absolute calibration of the well counter was determined by using a newly calibrated Am/Li source. This type of source was selected because its energy spectrum is very similar to that of delayed neutrons. The total number of fissions produced in the sample during a GODIVA irradiation was measured by a standard foil activation technique. Practically, a foil with the same composition as the samples was taped to the outside of the transfer tube at a position adjacent to that where samples were irradiated. After irradiation was completed, the foil was allowed to decay. Then the gamma activity of the ^{140}Ba, ^{140}La, and ^{99}Mo long-lived fission products was measured using a high purity germanium detector and the ^{140}La activity was compared to that of a calibration foil. The total DN yield results are:

$$\upsilon_d(^{235}\text{U}) = 0.0163 \pm 4.9\%,\ \upsilon_d(^{237}\text{Np}) = 0.0126 \pm 5.6\%$$

Group constant results are presented in Table A1.5 in Appendix 1.

4.5 Measurements made at Birmingham University

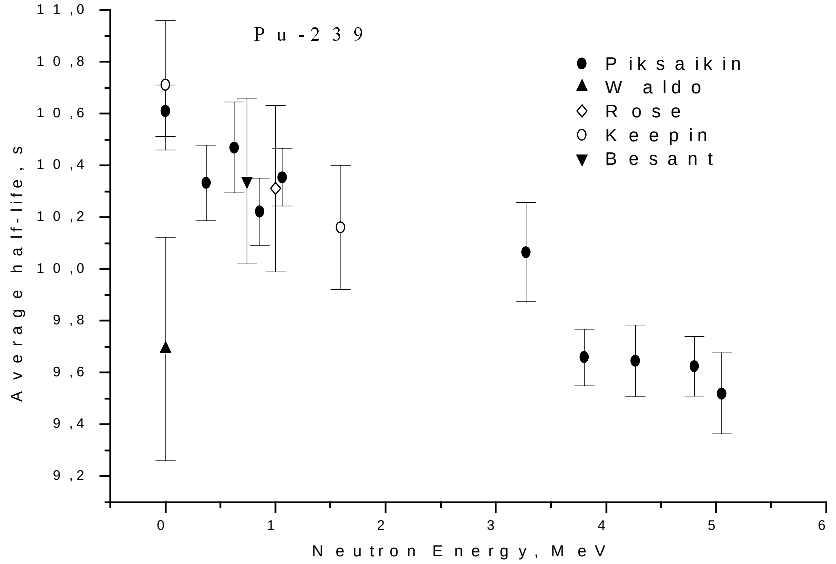
The measurement of the ^{235}U and ^{238}U absolute delayed neutron yield and group constants has been performed at the Birmingham University Dynamitron accelerator facility [74]. The University's accelerator was used to produce monoenergetic neutron fields from two reactions $T(p,n)^3He$ and $D(d,n)^3He$ in the two energy ranges of 1.4-3.0 MeV and 4.3-5.7 MeV. Samples of depleted and highly-enriched uranium were irradiated periodically. The DN counting system is partially made up of the University's well-calibrated de Pangher Long Counter. The second part of the DN counting system, completing a near 4π geometry, consists of an array of seven BF_3 counters mounted in a cadmium-covered polyethylene cylinder. The precise configuration of this counter was optimised using Monte Carlo calculations. Calibration of the two counters was carried out with an Am/Li neutron source because its energy spectrum is very similar to that of delayed neutrons. Unfortunately the original fission chamber used to monitor the fission rate was damaged during early testing of the sample transfer system and the calibration of a new chamber did not meet the desired accuracy. A new set of experimental calibrations is planned.

4.6 Development of methods of evaluation at IPPE Obninsk

Methods for the evaluation of the incident neutron energy dependence of delayed neutron time distributions from fission of some important actinides [75] have been developed at IPPE Obninsk. Studies of both the origins and the effects of fission product yield dependence on incident neutron energy were carried out [76,77]. A factorisation scheme to connect the energy dependence of DN yields with the variation of parameters determining the dependence of the charge-mass distribution of fission fragments on the energy of the neutron-inducing fission has been developed. This factorisation has been applied to evaluate the ^{237}Np DN yield incident neutron energy dependence up to 20 MeV, and the results up to 7 MeV were presented in Figure 1.

Recently, a measurement of ^{235}U and ^{239}Pu group constants was performed at IPPE Obninsk in the range from epithermal to 5 MeV, and for ^{238}U in the range 1 to 5 MeV, by Piksaikin, *et al*. [133]. The precursor average half-lives for ^{239}Pu are presented in Figure 3, and show a significant dependence on the incident neutron energy even within the range from 500 KeV to 3.5 MeV. The authors show that the energy dependence is linear in energy from epithermal to 5 MeV for ^{235}U and ^{239}Pu and for ^{238}U in the range 3 to 5 MeV.

Figure 3. ^{239}Pu precursor average half-lives in the range from epithermal to 5 MeV



4.7 Improvements to correlation methods and empirical models

There have been some important improvements to correlation methods and empirical models useful for estimating total DN yield data.

There have been improvements to Ronen's famous 2Z-N correlations [78]. Moreover, the independent and cumulative fission product yield data of England and Rider [33] have been used to update the results of Ronen's 2Z-N correlation and to correlate yields in spontaneous fission [79].

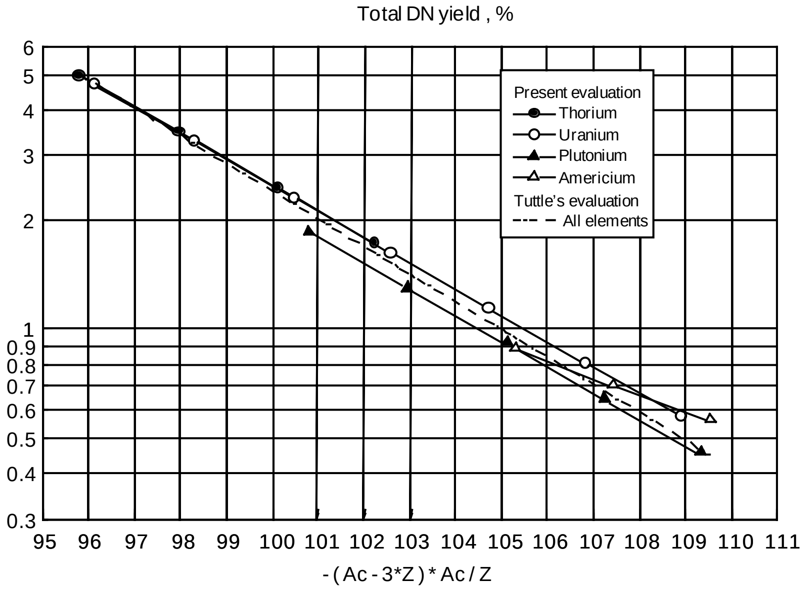
In order to obtain the parameters in the empirical equation correlating DNYs as a function of the parameter $-(A_c - 3Z)\cdot A_c/Z$ (A_c and Z being the mass number and the atomic number of the compound nucleus, respectively), Wahl [80], has added relatively more recent DN yield experimental results [81,82] to the least-squares fit proposed by Tuttle in 1979 [63]. The work has been extended to the empirical equation proposed by Waldo, as well as to an original modification of Waldo's equation.

With the aim of finding criteria for choosing the best set of DN parameters for various fissioning systems, an investigation of systematics and correlation properties of delayed neutrons from fast neutron-induced fission has been carried out by Piksaikin and Isaev [83].

The same $-(A_c - 3Z)\cdot A_c/Z$ parameter as that used by Tuttle (1979) and by Wahl (1993) to characterise the fissioning nucleus has been chosen. First, evident systematics applying to the average half-life of the DN precursors for different fissioning systems have been pointed out. Then, for the same fissioning systems, correlations between total DN yield values and average half-lives of the DN precursors have been used to obtain a set of DN yield systematics independent of those of Tuttle and Wahl.

Figure 4 shows that the whole set of total delayed neutron yield data cannot be represented by only one equation, as was done before this investigation, and that for each element (isotopes of a particular element) ν_d has its own dependence on the parameter $-(A_c - 3Z)\cdot A_c/Z$. The thorium and uranium isotopes have a similar dependence. The dependence of ν_d for Pu isotopes has the same slope as in the case of U and Th isotopes but has a parallel shift relative to the U and Th data. The dependence of ν_d on the parameter $-(A_c - 3Z)\cdot A_c/Z$ for the americium isotopes has a significantly different character. Therefore, according to these preliminary studies, the attempts to introduce more complicated parameters for the purpose of getting a better agreement with all experimental data look doubtful.

Figure 4. Dependence of total DN yields on the parameter $P = -(A_c - 3Z)\cdot A_c/Z$



4.8 Delayed neutron yield evaluations

An evaluation was carried out by Fort, *et al*. [57], at CEA Cadarache, including the use of the semi-empirical model of Lendel, *et al.* for the determination of the ^{239}Pu, ^{235}U, ^{238}U and ^{237}Np DN yield dependence on the incident neutron energy. The results for ^{239}Pu and ^{235}U were included in the JEF-2.2 nuclear data library. The calculated energy-dependent data for ^{235}U were normalised to the thermal value recommended by Kaneko, *et al.* [93]. For ^{239}Pu the normalisation was to the fast spectrum value of Tuttle [63]. The second chance, third chance, etc., fission were normalised to values derived using the systematics of Waldo, *et al.* [81].

In ENDF/B-VI and JENDL-3.2 a simple form of energy dependence has been adopted for ^{235}U, ^{238}U and ^{239}Pu, corresponding to values for first chance, second chance and third chance fission which vary linearly in energy throughout each of the ranges. This form of energy dependence follows the approach adopted by Tuttle, who proposed values at zero, 3 MeV, 7 MeV, 11 MeV and 14.5 MeV, with a variation linear in energy between these points. For ^{235}U and ^{239}Pu Tuttle proposed an increase of about 6% between thermal and 3 MeV followed by a more rapid decrease up to 7 MeV. This form of dependence is based on a range-wise linear fit to the monoenergetic measurements made by Krick and Evans [127].

The data adopted in ENDF/B-VI are even simpler in form, being the ENDF/B-IV data evaluated by Cox [128] for ^{235}U and ^{239}Pu and a (1978, unpublished) evaluation by Kaiser and Carpenter for ^{238}U. The values are constant in energy below 4 MeV, decrease linearly in energy up to 9 MeV and then remain constant to higher energies. The ^{238}U evaluation has a value below 4 MeV which is close to Tuttle's 1979 recommended fast spectrum value of 0.0439.

Table 6. Delayed neutron yield data in ENDF/B-VI

Energy (eV)	1.0E-5	4.0E+6	9.0E+6	2.0E+7
^{235}U DN yield	0.0167	0.0167	0.009	0.009
^{238}U DN yield	0.044	0.044	0.026	0.026
^{239}Pu DN yield	0.00645	0.00645	0.0043	0.0043

The ^{235}U and ^{239}Pu data in JENDL-3.2 vary linearly between thermal and about 3 MeV whereas the yield data for ^{238}U are constant below 3.5 MeV. The data for ^{239}Pu are Tuttle's incident neutron energy-dependent values (which are not precisely consistent with his thermal and fast spectrum values). One notes that the value for ^{238}U below 3.5 MeV is 9% higher than the value in

ENDF/B-VI, whereas the values for ^{235}U and ^{239}Pu at thermal energies are both about 4% lower. The JENDL-3.2 data for ^{238}U have also been adopted in JEF-2.2.

Table 7. Delayed neutron yield data in JENDL-3.2

Energy (eV)	1.0E-5	2.53E-2	3.30393E+6	6.89961E+6	1.3519E+7
^{235}U DN yield	0.0160	0.0160	0.0171875	0.0096	0.0096
Energy (eV)	1.0E-5		3.5E+6	7.0E+6	2.0E+7
^{238}U DN yield	0.0481		0.0481	0.0360	0.0188
Energy (eV)	1.0E-5	2.53E-2	3.0E+6	7.0E+6	1.1E+7
^{239}Pu DN yield	0.00622	0.00622	0.00659	0.00480	0.00480

When averaged in a reactor spectrum the values given in Table 8 result. These values are approximate because they vary with the particular spectrum. However, this variation is small – less than 1%. It will be seen that the differences between the thermal and fast reactor spectrum-averaged values are quite small in these evaluations. The JEF-2.2 values for thermal and fast reactor fission in ^{235}U and ^{239}Pu are within about 1% of the ENDF/B-VI values whereas the value for ^{238}U is the high value adopted from JENDL-3.2, being about 9% higher than the ENDF/B-VI value.

The values recommended by Tuttle (1975 and 1979) and by Blachot, *et al.* [1] are also included in the table for comparison purposes, along with the fast reactor spectrum-averaged values obtained by D'Angelo [86] in an integral measurement adjustment study. The value obtained by Kaneko, *et al.* [93] for ^{235}U thermal, on the basis of the SHE series of integral measurements, is also given. This has a quoted accuracy of 1.2%.

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 about this energy in the mean energies of the different fast spectrum systems included in the integral data studies.

Some of the recent measurements of total DN yields reported above have also been included in Table 8. They are broadly consistent with the data in the different evaluations. We note that the thermal value for ^{235}U in JENDL-3.2 is low compared with the value (of beta) measured by Kaneko, *et al.* [93]. However, it is consistent with the measurement made at Texas A&M.

Table 8. Thermal and fast reactor spectrum-averaged values

	^{235}U thermal	^{235}U fast	^{238}U fast	^{239}Pu thermal	^{239}Pu fast
JEF-2.2	0.01654	0.01658	0.0468*	0.00647	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) [66]	0.01654±2.5%	0.01714±1.3%	0.0451±1.4%	0.00624±3.8%	0.00664±2.0%
Tuttle (1979) [63]	0.01621±3.1%	0.01673±2.1%	0.0439±2.3%	0.00628±6.0%	0.00630±2.5%
Blachot (1990) [1]	0.0166±3.0%	0.0166±3.0%	0.045±4.5%	0.00654±4.0%	0.00654±4.0%
D'Angelo (1990) [86]		0.0165±2.0%	0.0457±3.8%		0.0066±2.9%
Kaneko (1988) [93]	0.01650±1.2%				
Piksaikin (1997) [61]		0.0168±5%**			
Parish (1997) [4]	0.0159±2.5%	0.0167±4.8%			
Borzakov (1997) [65]				0.00686±5%	
Sakurai and Okajima (2002) [130]	0.01586	0.0160±1.8%	0.0456±3.6%	0.00638±3.6%	0.00642±3.6%
Fort, *et al.* (2002) [131]***	0.01621±1.3%	0.01658±1.6%	0.0469±2.4%	0.00651±1.7%	0.00656±2.6%
Values proposed in Appendix 2	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*. [131]. The value used by Okajima, *et al*. [130], starting from the same energy-dependent data, is 0.0471, this being the appropriate value for the FCA XIX series of fast spectrum cores.

** The 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 values given here are those derived in Appendix 2 and are not precisely the same as the spectrum-averaged values given by Fort, *et al*. in their paper. The uncertainties given here are relative and do not take into account all sources of uncertainty.

Finally the table includes the values derived from the adjusted energy dependent data of Fort, *et al*. [131] and of Sakurai and Okajima [130], as described in Appendix 2, together with the recommended weighted average values also proposed in Appendix 2. Because of their widespread use, it is interesting to recall 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 (1979) values for ^{235}U, 3% to 4% larger for ^{239}Pu and 5.6% larger for ^{238}U.

4.9 Methods for deriving delayed neutron spectra for time groups

A least-squares method to decompose composite spectra measured at different delay time intervals following fission into group-wise DN spectra has been developed [84,85]. The method has been used to obtain six-group spectra from the University of Lowell measured spectra. Different tests have been made to evaluate the quality of the decomposition method. The conclusion is that the experimental uncertainties in the measured composite spectra do not lead to unstable solutions (when small changes in the measured spectra result in markedly different group spectra). It has also been verified that a more likely cause of instability is the approximation of using the classical six-group structure to describe the time variation of the DN energy spectrum. This conclusion confirmed the interest in the work carried out at Los Alamos to re-define the structure used to represent DN time dependence by means of group data.

5. In-pile measurements, DN data sensitivity analyses and data validations

5.1 The programmes of measurements of β_{eff} in fast spectrum systems studied in MASURCA and FCA and in thermal spectrum systems

Concerning activities at the integral level, the need for further experimental information on the in-pile reactivity scale was well recognised [86]. A number of other studies have also pointed out inadequacies in the data [8-11]. Two series of international benchmarks were defined to measure β_{eff} in fast reactor spectra using different techniques and on complementary cores. The first series of measurements was at the MASURCA fast facility at CEA, Cadarache and the second at the FCA fast facility at JAERI/Tokai-Mura [87-89]. The results obtained in the experimental programmes are summarised in a paper by Okajima, *et al.* [90]. The measurements made in FCA have been described in more detail in papers published in a special issue of *Progress in Nuclear Energy* (Vol. 35. No. 2, 1999).

Measurements were made in two MASURCA (BERENICE) cores, R2 and ZONA2 and three FCA cores, XIX-1, -2 and -3. These cores all have fast spectra and contain the following fuels and principal diluents:

R2	U oxide fuel	(30% enriched)	Steel, sodium
ZONA2	Pu/U oxide fuel	(25% enriched)	Steel, sodium
XIX-1	U metal fuel	(93% enriched)	Graphite, steel
XIX-2	Pu/U(nitride) fuel	(23% enriched)	Steel, sodium
XIX-3	Pu metal fuel	(92% fissile)	Steel

The groups which participated in these experiments were: CEA Cadarache (France), IPPE/Obninsk (Russia), JAERI (Japan), KAERI (Korea), LANL (USA) and Nagoya University (Japan). The β_{eff} values were measured within an experimental error of about ±3%. The techniques used were:

- cf. source;
- noise;
- Rossi-α;
- modified Bennet;
- Nelson number.

These measurements differ from earlier ones in that several different techniques have been used for the measurements made on each core and the measurements have been made by different teams. They are therefore proposed as benchmark measurements. It can be noted that the results are broadly consistent with the measurements made in the SNEAK [91] and ZPR [92] series of measurements (although perhaps about 2% smaller on average).

Intercomparisons of the measurements made in the benchmark programme provide an insight into the accuracy of the different methods. Two groups have 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-α measurement made in R2 comprised measurements made at two different reactivity levels and gave values which differ by 3%. There are additional sources of error 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 (and a much smaller uncertainty has been assumed in the study made by Fort, *et al*. [131]).

Measurements made using the noise technique can be compared with the mean values of the measurements made in a core using the 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 introduces an uncertainty in the measured β_{eff} values of about ±1.3%.) We note, however, that a much smaller uncertainty than this figure of ±2.5% has been assumed for the noise measurements made in the thermal spectrum MISTRAL cores (±1.6%) studied in the EOLE facility at Cadarache.

Further intercomparisons of the different techniques would be helpful in maintaining confidence in the use of the earlier measurements made in SNEAK and ZPR where a single technique (cf. source or noise) was used.

Thermal spectrum measurements have been made for uranium-fuelled systems in the SHE series of critical experiments [93]. More recently, effective delayed neutron fraction measurements have been made in both UOX- and MOX-fuelled PWR-type lattices in the MISTRAL programme carried out in the EOLE facility at Cadarache [94] (MISTRAL-1 and -2). The effective delayed neutron fraction for light-water moderated cores has also been measured on the TCA critical assembly in a low-enriched UO_2 core and in three MOX cores. Only relative result comparisons have been published for the MOX-fuelled cores [95]. The values calculated using JENDL-3.2 are slightly larger than the measured values, but within the uncertainty range for all with the exception of the UO_2 core measurement for which the difference is about 3%. The measurement made in this UOX core has been included in the adjustment study carried out by Sakurai and Okajima [130].

Improvements have been made to the experimental techniques used for in-pile measurements of the integral kinetic parameter, the effective delayed neutron fraction (β_{eff}) [96-102] and to the methods used in the final interpretation of these measurements in terms of delayed neutron yield data [103-105].

5.2 Validation of total delayed neutron yields using the beta-effective measurements

The total DN yield evaluations for the major isotopes can be validated by comparing calculated reactivity scale values with the corresponding in-pile experimental results. The validation and improvement of total delayed neutron yield data for ^{239}Pu, ^{235}U and ^{238}U, and the incident neutron energy dependence, has been carried out at the CEA. The experimental information in fast spectra coming from the BERENICE (MASURCA) and the FCA XIX campaigns, together with the earlier ZPR and SNEAK results, and the SHE and MISTRAL campaigns in thermal spectra, has been used [106,107]. The validation studies which have been carried out by Fort, *et al.* [131] at CEA Cadarache are presented in document No. 1 on the attached CD-ROM.

Validation of ^{239}Pu, ^{235}U and ^{238}U total delayed neutron yield data has also been carried out at JAERI, by analysing the XIX and BERENICE fast spectrum measurements and the thermal spectrum measurement made in TCA [130]. A good agreement is found between the measured values and the JENDL-3.2 calculated β_{eff} results. This analysis broadly confirms the main conclusions of the validation work carried out at CEA Cadarache. In particular, the integral data support a higher value for the total DN yield for ^{238}U than that adopted in ENDF/B-VI and given in some previous evaluations at the macroscopic level, in particular Refs. [63,67,80].

The results of the studies carried out by Fort, *et al*. [131] and by Sakurai and Okajima [130] are summarised in Appendix 2 and conclusions drawn from the studies are given in Section 6.

5.3 Other programmes of integral measurements and validation studies

Many in-pile measurement campaigns and experimental simulations originally made to obtain key parameters for specific reactor designs have allowed to test macroscopic DN data [9-12,109-116]. As already mentioned, in some cases these studies pointed out important inconsistencies in the DN data in some data libraries, in particular in the six-group constants included in ENDF/B-VI and in JEF-2.2.

An investigation has been made by D'Angelo and Filip [117] of the effects of the DN yield incident neutron energy dependence on the calcula tion of the β_{eff} reactor-kinetics parameter.

5.4 Estimations of the uncertainties in calculations of β_{eff}

An overall uncertainty analysis of the calculated value of β_{eff} for a typical fast reactor [118,119] has been carried out in Japan. Besides the most important impact of the DN yield data, these analyses also take into account the uncertainty contributions due to the fission cross-sections and to the incident neutron energy dependence of DN yields.

The target accuracy which has been proposed for β_{eff} calculations is ±3% (1 s.d.). 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 derived from the SHE programme and the TCA measurement needs to be understood.

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 is reported that for the U/Pu-fuelled core studied in TCA there is agreement between measurement and the JENDL-3.2 calculation. The ^{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 be -3%.

More measurements on thermal systems and analyses of existing measurements are needed to provide 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*. [131] (see document No. 1 on the CD-ROM) 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 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 be 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*. [90]. A similarly good agreement is found by Sakurai and Okajima [130] (see also Appendix 2) in calculations made for the MASURCA and FCA benchmark measurements, using a data set based on JENDL-3.2. We conclude that for fast spectrum systems fuelled with ^{235}U, ^{238}U and ^{239}Pu the β_{eff} value calculated using the recommended values of the yields will have uncertainties of between ±2% and ±3%. (The agreement found when using ENDF/B-VI total delayed neutron yield data is less good, reflecting the effect of the lower delayed neutron yield for ^{238}U.)

Comparisons have been made for the FCA cores between ENDF/B-VI and JENDL-3.2 delayed neutron spectra and the effect is to change β_{eff} by about 0.6% or less. The spectra adopted in JENDL-3.2 were those obtained by means of summation calculations by Saphier, *et al*. [137] (67 precursors) whereas in ENDF/B-VI the more recent summation calculations made by Brady and

England (271 precursors) provided the spectra [44]. A comparison has also been made between the JEF-2.2 and ENDF/B-VI DN spectra for R2 and ZONA2, and this has given similar changes.

If there are errors in the calculations of fission rate ratios and fission rate distributions these errors will be reflected in the calculated value of β_{eff}. In particular, an error in the calculation of the $^{238}U/^{239}Pu$ fission ratio will affect the value of β_{eff} calculated for a Pu/U-fuelled system. It is important to check the accuracy of calculations of such ratios. Errors in the calculation of the adjoint flux or importance spectrum can also have an effect by introducing an error in the calculation of the relative importance of delayed and prompt neutrons. It is best to check the accuracy of a calculational scheme by calculating measured values of β_{eff} for systems similar to those for which predictions are to be made. However, we note that the differences are less than about 1% between calculations made using ERALIB1 and JENDL-3.2 together with the same set of yield values (ENDF/B-VI).

5.5 The representation of time dependence

The eight-group representation

A new eight-group reference structure for group constants has been defined at Los Alamos in co-operation with IPPE Obninsk [120-123]. This work was agreed to be an important task by the Advisory Committee of the Colloquy on Delayed Neutron Data meeting held at Obninsk (Russia) on 9-10 April 1997. This uses the same set of eight-group half-lives for all fissioning systems, with the half-lives adopted for the three longest-lived groups corresponding to the three dominant long-lived precursors: ^{87}Br, ^{137}I and ^{88}Br. Two main reasons for adopting this new DN group data structure can be briefly mentioned here:

1. the need for a more consistent description of the DN emission from the longest-lived precursors to avoid distortions in the reactivity measurement analysis (today it is recognised that the half-lives used in Keepin’s six-group structure do not accurately reproduce the asymptotic die-away time constants associated with the three longest-lived dominant precursors);

2. the advantage of using a single set of precursor half-lives (for all fissile isotopes and incident neutron energies) in calculations of reactor kinetics.

The first part of the work consisted of a comprehensive literature survey to ascertain the various group parameters that have been reported in the open literature during the last 50 years [120]. Two hundred thirty-eight (238) individual experimentally derived sets of delayed neutron group constants for 20 different fissionable isotopes have been reported. In the second part of the work, the 238 experimental sets were expanded into a higher-order model based on a consistent eight-group set of half-lives [121]. The work is described in LA-UR-98-1619 (document No. 3 on the CD-ROM) and the associated work to derive the eight-group spectra in LA-UR-99-4000 are summarised in Appendix 3.

For the major actinides the experimentally derived parameters from which the eight-group relative abundances have been calculated are as follows:

^{235}U thermal	Keepin, *et al*. (1957) [138]
^{235}U fast	Piksaikin, *et al*. (1997) [61]
^{238}U fast	Keepin, *et al*. (1957) [138]
^{239}Pu thermal	Keepin, *et al*. (1957) [138]
^{239}Pu fast	Besant, *et al.* (1977) [139]

The values are given at thermal energy, fast energy and high energy. Piksaikin, *et al*. [133] point out that the incident neutron energy dependence they find for the average half-life of precursors justifies linear interpolation in energy being used to calculate the group relative abundances for a particular reactor fission rate energy spectrum from the values given at thermal and fast energies.

The eight-group data structure has also been discussed by Svarny [124].

The spectra for the eight time groups have been calculated from the spectra for the individual precursors. ENDF/B-VI contains energy spectra (grouped in 10 keV intervals) for 243 precursors. Using the P_n values of Mann, *et al*. [125] and the yields of England and Rider [33] the spectra have been calculated for the eight time groups in the Hansen and Roach 16 energy group structure. The recommended relative abundances and 16-group energy spectra are given in Appendix 3.

The mean energies of the spectra in each of the eight groups for the major actinide isotopes are as shown in Table 9.

Table 9. Mean energies of the eight-group spectra (in keV) for the major actinide isotopes

Data taken from LA-UR-99-4000

Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Sum**
Half-life (secs)	55.6	24.5	16.3	5.21	2.37	1.04	0.424	0.195	
^{235}U thermal	211	612	269	441	516	512	616	619	494
^{235}U fast	211	609	265	453	542	534	603	572	501
^{238}U fast	211	613	289	433	539	515	671	569	535
^{239}Pu thermal	211	617	289	418	475	473	555	549	481
^{239}Pu fast	211	615	284	421	484	477	586	523	488

Studies of six-group and seven-group representations

A new seven-group structure [126] has also been defined at Los Alamos. Also in this case, the aim was to propose a single set of decay constants that would apply to all fissionable isotopes and be independent of the incident neutron energy. In order to identify the set of half-lives, precursors that are dominant contributors to the DN activity have been identified. As for the new eight-group structure mentioned above, the half-lives of the three longest-lived dominant precursors have been chosen to define three-group half-lives of the new structure. A linear fit technique has been used to obtain the seven-group abundances either directly from the results of DN activity measurements (^{235}U and ^{237}Np) or from results already interpreted in the traditional six-group structure.

Moreover, as many existing computer codes assume six groups, a six-group representation has also been formulated using the geometric average of the ^{137}I and ^{88}Br decay constants in the traditional Group 2. In principle, these six-group data could satisfy the needs of those commercial organisations that have expressed reluctance to make a transition from six DN groups to seven or eight groups. But a test on ^{235}U thermal data showed that the performance of these new six-group data might not be good in the cases of transients involving strong negative reactivity insertions. Also the seven-group data set was less good than the eight-group set in the analysis of strong negative reactivity insertion experiments.

Representation of time dependence in current evaluated data libraries

Time dependence is represented in JENDL-3.2, ENDF/B-VI and JEF-2.2 by the fast spectrum six-group parameters. Incident neutron energy dependence cannot be represented in the files. Keepin's values were adopted in JENDL-3.2 whereas in ENDF/B-VI the Brady and England [44] six-group parameters, obtained by means of summation calculations, were adopted. These ENDF/B-VI data have been found to be less satisfactory than Keepin's data. In JEF-2.2 the data for ^{235}U and ^{239}Pu are a mixture of the two sources (half-lives from one source and relative abundances from the other source) and are not suitable for use.

6. Concluding remarks

The researches related to the improvement of DN data, either carried out in the frame of the subgroup or at least monitored during the period of about ten years that this international committee has been active, have been briefly reviewed. Many improvements have been made to DN data at the individual precursor (or microscopic) level, yields, P_n values and half-lives, and these can be included in the databases and models used by the different nuclear data file projects and hence used to obtain DN data by means of summation techniques. Specific sensitivity studies have shown, however, that the aggregate precursor (or macroscopic) measurements, evaluations and validations still provide, whenever available, more precise DN data for use in reactor calculations. Nevertheless, a much higher precision on DN data calculated by summation techniques is expected in the near future, thanks to the more precise methods for making microscopic data measurements that are being developed at the neutron-rich isotope beam facilities.

Today, to improve the precision of calculations of delayed neutron fractions (β_{eff}), the main fissile isotope DN yield data evaluated at the macroscopic level and validated on the available in-pile measurements have to be recommended for reactor calculations, as described in Appendix 2. As a particular result, one notes that high values of the ^{238}U total DN yield are recommended on the basis of data adjustments made to fit the β_{eff} measurements, an evident discrepancy between the in-pile measurement information and some previous evaluations which give a significantly lower value for the yield [63,67,81] and the data adopted in ENDF/B-VI. The total yield data recommended in Appendix 2 are the following:

Table 10. Summary of recommended values for total delayed neutron yields

^{235}U thermal	^{235}U fast	^{238}U fast	^{239}Pu thermal	^{239}Pu fast
0.0162	0.0163	0.0465	0.00650	0.00651

These values are averages of the adjusted values calculated in Appendix 2 based on the results of the studies made by Fort, *et al*. [131] and by Sakurai and Okajima [130]. It is considered that using these averaged values the target accuracy of ±3% (1 s.d.) will be achieved in β_{eff} calculations, and for fast spectrum systems the accuracy could be closer to ±2% (1 s.d.). The possible additional sources of uncertainty due to inaccuracies in relative fission rate and fission rate distribution calculations, and calculations of the relative importances of delayed neutrons, could increase this figure. We note, however, that the agreement between calculations made using ERALIB-1 and JENDL-3.2 and the same set of yield data is within 1%.

Based on these recommended thermal and fast reactor spectrum-averaged yield values, energy-dependent values suitable for inclusion in the nuclear data libraries are proposed at the end of Appendix 2.

For the DN group constants and spectra, the subgroup recommends a new eight-group precursor structure to improve both the analysis of the in-pile reactivity measurements and the reactor kinetics calculations. The new structure is defined on the basis of current knowledge of the half-lives of the dominant precursor isotopes. In particular, the half-lives of the first three groups have been fixed at the half-lives of the three longest-lived dominant precursors. From the reactor physics point of view, the method used to expand the experimental results from the classical six-group structure to the new eight-group structure conserves the in-pile positive reactivity results of the stable period measurements. Moreover, the new eight-group structure is characterised by the same set of half-lives for all fissioning isotopes and for fission induced by neutrons of different energies. Therefore, data in the new structure can be used without approximation in reactor kinetics calculations by solving only nine differential equations (eight for the precursors in different groups and one for the neutron density). On the contrary, Keepin's six-group structure (characterised by different sets of half-lives for different isotopes and for different incident neutron energies) in principle required the solution of six differential equations for each fissioning isotope and for each different incident neutron energy. Some sets of six-group data having the same six half-lives for all isotopes have been derived from Keepin's data but these involve approximations.

The recommendations of the subgroup are presented in Appendices 2 and 3. They provide a significant improvement to the classical reactor calculations relevant to the reactivity scale and its time dependence. But there is a need for a continuing effort on delayed neutron data. This will be mainly directed towards satisfying new requirements emerging from the current trends in reactor technology, in particular data for isotopes of interest for transmutation applications (^{237}Np, Am and Cm isotopes) and for the Th fuel cycle (^{232}Th and

^{233}U). Moreover, the problem of the dependence of yields on the incident neutron energy below 4 MeV remains open; in particular the latest investigations indicate that the variation is significant for ^{237}Np. Finally, recent measurements at IPPE Obninsk on the dependence of ^{239}Pu delayed neutron precursor average half-life on incident neutron energy have pointed out the interest of further investigations of the delayed reactivity scale time-dependence. The target of these further investigations should be to verify the possibility of recommending DN group constants as an explicit function of the incident neutron energy.

To significantly reduce the present uncertainties in the total yield data for the major actinides new measurements should achieve an accuracy of ±2% or better. For relative measurements of the energy dependence an accuracy of ±1% should be aimed for. For the secondary isotopes the uncertainties are larger and more measurements having a lower precision would be useful. For the more exotic systems which are presently being studied, with contributions from intermediate energies being significant in some designs, more information could be required about the energy dependence at MeV energies. Regarding 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 information to be obtained about energy dependence.

There appears to be a difference of about 2% between the older (SNEAK and ZPR) measurements of β_{eff} and the benchmark series of measurements. Further intercomparisons of techniques and measurements made on cores similar to the older cores would be helpful in understanding this difference and would also give confidence in the high accuracy which has been assigned to the recent thermal reactor measurements.

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APPENDIX 1

Measurements of the Group Parameters Representing Time Dependence

Table A1.1. Group constants measured at IPPE Obninsk at an incident neutron energy of about 1.15 MeV

	1	**2**	**3**	**4**	**5**	**6**
	^{235}U					
A_i	0.037±0.002	0.226±0.006	0.187±0.015	0.398±0.0017	0.0126±0.008	0.025±0.001
T_i	55.30±0.82	21.88±0.41	6.14±0.43	2.35±0.09	0.628±0.041	0.174±0.009
	^{237}Np					
A_i	0.031±0.001	0.246±0.007	0.167±0.007	0.397±0.009	0.144±0.007	0.016±0.001
T_i	55.32±0.94	22.71±0.24	6.53±0.20	2.37±0.060	0.483±0.027	0.202±0.010

A_I denotes the relative abundance and T_i the half-life (in secs).

Table A1.2. Group constants measured for ^{235}U, ^{237}Np, ^{241}Am and ^{243}Am at the D-2 location of TAMU

For ^{235}U, ^{241}Am, ^{243}Am and ^{237}Np, the fractions of fissions induced by neutrons with energies below 10 eV were: >95%, 82%, 16% and 3% respectively

	1	**2**	**3**	**4**	**5**	**6**
	^{235}U					
A_i	0.036±0.006	0.239±0.039	0.195±0.033	0.390±0.065	0.0111±0.018	–
T_i	55.5±4.0	19.3±1.1	6.24±0.39	2.31±0.039	0.630±0.014	–
	^{237}Np					
A_i	0.040±0.002	0.233±0.017	0.19±0.01	0.322±0.027	0.193±0.007	–
T_i	53.7±2.5	21.4±0.73	6.60±0.13	2.03±0.077	0.815±0.058	–
	^{241}Am					
A_i	0.36±0.002	0.309±0.015	0.195±0.008	0.331±0.039	0.110±0.005	–
T_i	56.8±2.8	21.8±1.1	6.24±0.39	2.31±0.13	0.779±0.02	–
	^{243}Am					
A_i	0.025±0.0012	0.300±0.0098	0.227±0.0074	0.395±0.015	0.053±0.0037	–
T_i	52.9±0.81	22.3±0.64	6.48±0.42	2.14±0.14	0.758±0.026	–

Table A1.3. ^{235}U, ^{237}Np and ^{243}Am group constant measurements at the D-3 location of the TAMU reactor

The fraction of fissions below 100 keV for ^{235}U, ^{237}Np, and ^{243}Am were 0.41, 0.002 and 0.003, respectively

	1	**2a**	**2b**	**3**	**4**	**5**
				^{235}U		
A_i	0.032±0.001	0.133±0.007	0.109±0.005	0.260±0.010	0.257±0.010	0.180±0.011
T_i	55.5±0.9	24.5±0.3	16.5±0.2	4.39±0.06	2.16±0.03	0.712±0.012
				^{237}Np		
A_i	0.030±0.002	0.160±0.010	0.094±0.004	0.320±0.018	0.284±0.014	0.0875±0.014
T_i	55.9±1.4	24.5±0.61	17.0±0.3	4.20±0.05	1.65±0.02	0.830±0.030
				^{243}Am		
A_i	0.016±0.005	0.202±0.010	0.061±0.005	0.235±0.014	0.330±0.015	0.126±0.013
T_i	55.9±1.8	24.5±0.8	16.5±0.4	4.78±0.07	0.175±0.003	0.465±0.012

Table A1.4. **^{237}Np and ^{243}Am group constants. Preliminary extended results (Position D-3, TAMU reactor).**

Group i	**^{237}Np**		**^{243}Am**	
	$T_{1/2}$ (sec)	**a_i**	**$T_{1/2}$ (sec)**	**a_i**
1	55.90±1.35	0.030±0.002	55.90±1.80	0.017±0.005
2a	24.49±0.61	0.160±0.011	24.49±0.79	0.226±0.011
2b	16.86±0.33	0.083±0.004	16.70±0.36	0.088±0.006
3	4.47±0.06	0.285±0.016	4.590±0.06	0.205±0.011
4	1.75±0.03	0.323±0.013	1.768±0.03	0.335±0.011
5	0.820±0.029	0.087±0.096	0.774±0.035	0.088±0.009
6	0.272±0.003	0.032±0.008	0.283±0.005	0.041±0.008

Table A1.5. ^{235}U and ^{237}Np group constant results in the GODIVA-4 fast facility flux

Mean energy about 1.3 MeV

	1	**2**	**3**	**4**	**5**	**6**
	^{235}U					
A_i	0.039±0.001	0.235±0.005	0.207±0.008	0.381±0.011	0.0114±0.005	0.024±0.001
T_i	54.6±0.43	22.0±0.28	5.92±0.32	2.23±0.08	0.506±0.019	0.181±0.0054
	^{237}Np					
A_i	0.032±0.003	0.238±0.006	0.175±0.008	0.360±0.017	0.150±0.014	0.045±0.006
T_i	56.3±4.1	27.9±0.43	7.14±0.51	2.34±0.11	0.758±0.048	0.217±0.009

APPENDIX 2

Recommended Total Delayed Neutron Yields, ν_d, for ^{235}U, ^{238}U and ^{239}Pu

The recommendations are based on analyses of β_{eff} values measured in the fast spectrum systems MASURCA (BERENICE), FCA (XIX), SNEAK and ZPR, and in the thermal spectrum systems EOLE (MISTRAL), TCA and SHE.

In a study presented in 1990, D'Angelo [86] analysed the β_{eff} measurements made in a series of SNEAK and ZPR fast critical assemblies (four SNEAK assemblies and six ZPR assemblies) to derive improved fast spectrum-averaged yields. In 1997 D'Angelo and Filip extended this study to include the measurements made in the two MASURCA cores, R2 and ZONA2. The data adjusted in these studies were the fast spectrum yield values included in the French CARNAVAL-IV data set, these values being similar to those recommended by Tuttle in 1975.

The more recent studies by Fort, *et al.* [131] (see document No. 1 on the attached CD-ROM) have generalised the approach by treating the energy dependence and adjusting the yield values in five energy groups. The yields adjusted are the JEF-2.2 values. The delayed neutron yield data for ^{235}U and ^{239}Pu were evaluated by Fort and Long [57], whereas the data for ^{238}U were adopted from JENDL-3.2. In addition to the systems analysed by D'Angelo and Filip two of the three FCA XIX fast reactor cores (cores 1 and 3) were included, together with three thermal reactor systems (SHE-8, MISTRAL-1 and MISTRAL-2).

The measured β_{eff} values have also been revised by Fort, *et al*. In particular the Diven factors used in the derivation of the measured values for the ZPR cores and for the earlier interpretation of measurements made in the R2 and ZONA2 cores have been revised. These are then consistent with the values used in the interpretation of the CEA measurements made in the FCA XIX-1 and -3 cores and with the values used by the other groups making measurements in the XIX cores. The spatial fission rate distributions involved in the interpretation of the R2 and ZONA2 measurements have also been revised and are based on calculations made using the ERALIB1 data set. These distributions are then consistent (in the data used) with the calculated β_{eff} values with which the measured values are compared. The uncertainties in the measurements have also been reassessed and the correlations between the uncertainties in the different measurements made in the same core and in different cores have been treated.

The ERALIB1 data set, which has been used by Fort, *et al.* to calculate the fluxes and reaction rates, is a CEA development of a cross-section set based on JEF-2.2, adjusted on the basis of an analysis of integral measurements. These reaction rates are combined with the delayed neutron yield data in JEF-2.2 to obtain the β_{eff} values. Because the measured values are being compared with values calculated using the ERALIB1 adjusted cross-section set it is considered that no allowance need be made for uncertainties in the fission rate calculations used in deriving the measured values and calculated values of β_{eff} with which they are compared.

All of the calculated values are within 3% of the measured values (or within 1 s.d. of the measured value when the discrepancy is larger than 3%). The comparisons therefore give confidence (at the ±3% level) in the use of JEF-2.2 yield data.

Starting from the delayed neutron data in the JEF-2.2 library the sensitivities of the calculated values of β_{eff} to changes in the delayed neutron data, in five energy groups, have been calculated by Fort, *et al*. Based on these sensitivities the delayed neutron data have been adjusted in the five energy groups to improve the agreement between the calculated and measured values of β_{eff}. The adjustments have been made in such a way as to minimise the sum of squares of the residual deviations (between measured and calculated values) and the changes made to the delayed neutron yield data, relative to the assumed uncertainties in the data.

The adjustments and the estimates of the accuracy of the adjusted data depend on the estimated uncertainties in the measured values of β_{eff}, in the calculations of relative fission rates and delayed neutron importances, in the unadjusted delayed neutron data and in the energy dependence of the total yields. Different assumptions about the uncertainties could result in different adjustments and associated accuracy estimates. Fort, *et al*. have used Lendel's model to calculate the energy dependence for ^{235}U and ^{239}Pu and to estimate the uncertainty in this energy dependence.

The five group values before and after adjustment are as displayed in the following tables.

Table A2.1. Total delayed neutron yields before adjustment (JEF-2.2 data) and the assumed uncertainties

Study by Fort, et al., see document No. 1 on the attached CD-ROM

		^{235}U	**^{238}U**	**^{239}Pu**
Group 1	**0-10 keV**	1.654E-2±3.0%	4.810E-2±6.0%	6.471E-3±4.0%
Group 2	**10-500 keV**	1.656E-2±3.0%	4.810E-2±6.0%	6.414E-3±4.0%
Group 3	**0.5-4 MeV**	1.681E-2±4.0%	4.809E-2±7.0%	6.579E-3±5.0%
Group 4	**4-7 MeV**	1.539E-2±6.0%	4.438E-2±9.0%	6.085E-3±7.0%
Group 5	**7-20 MeV**	1.127E-2±7.0%	3.567E-2±10.0%	3.797E-3±8.0%

Table A2.2. Total delayed neutron yields after adjustment and the associated uncertainties

		^{235}U	**^{238}U**	**^{239}Pu**
Group 1	**0-10 keV**	1.621E-2±1.3%	4.810E-2±5.9%	6.495E-3±1.7%
Group 2	**10-500 keV**	1.663E-2±1.6%	4.808E-2±5.9%	6.535E-3±2.6%
Group 3	**0.5-4 MeV**	1.687E-2±3.5%	4.818E-2±2.4%	6.659E-3±4.1%
Group 4	**4-7 MeV**	1.538E-2±5.9%	4.430E-2±8.4%	6.115E-3±6.8%
Group 5	**7-20 MeV**	1.127E-2±6.9%	3.544E-2±9.8%	3.800E-3±7.9%

From these five group values we can calculate corresponding thermal and fast reactor spectrum-averaged values. The unadjusted average values are the mean values for the systems studied by Fort, *et al*. (see Ref. [107]). The percentage changes to these spectrum-averaged values have been calculated by weighting the percentage adjustments given in Table A2.3 with the sensitivity coefficients of β_{eff} values (for a chosen system) to changes in the group yields, (as given by V. Zammit-Averlant in [107], for MISTRAL-2, in a private communication from O. Litaize).

Table A2.3. Percentage adjustments

		^{235}U	**^{238}U**	**^{239}Pu**
Group 1	**0-10 keV**	-2.00%	+0.00%	+0.38%
Group 2	**10-500 keV**	+0.43%	-0.02%	+1.88%
Group 3	**0.5-4 MeV**	+0.33%	+0.18%	+1.21%
Group 4	**4-7 MeV**	-0.05%	-0.18%	+0.49%
Group 5	**7-20 MeV**	-0.02%	-0.64%	+0.09%

The choice of fast spectrum system for weighting the ^{235}U five-group data has a significant effect on the calculated value of the averaged change. It depends on the sensitivity to the Group 1 adjustment, below 10 keV, which is mainly determined by the fit to the thermal spectrum systems (MISTRAL-1 and SHE-8). The 0.4% increase in the Group 2 value is perhaps partly to compensate for this 2% decrease below 10 keV, which affects several of the fast spectrum systems. We note that the changes for the uranium-fuelled fast spectrum systems included in the study by Fort, *et al*. are as follows: ZPR U9 +0.4%, SNEAK 9C1 +0.20%, MASURCA R2 +0.09%, FCA XIX-1 -0.77%, ZPR UFeRef -0.31%, these last two systems being fuelled with highly-enriched uranium. Such a strong variation in the values seems unphysical and is a consequence of this step change in the yield by about 2.6% at 10 keV. We have chosen to assume in what follows that there is no significant change to the fast spectrum-averaged yield for ^{235}U.

Table A2.4. Group sensitivities for the chosen systems

	^{235}U thermal	^{235}U fast	^{238}U fast	^{239}Pu thermal	^{239}Pu fast
Chosen system	**MISTRAL-1**	**MASURCA R2**	**MASURCA ZONA2**	**MISTRAL-2**	**MASURCA ZONA2**
Group 1	0.87	0.10	0.00	0.97	0.06
Group 2	0.01	0.49	0.00	0.01	0.24
Group 3	0.01	0.17	0.39	0.02	0.11
Group 4	0.00	0.01	0.07	0.00	0.01
Group 5	0.00	0.00	0.02	0.00	0.00
Total	0.89	0.45	0.48	1.00	0.42
Averaged change (%)	-2.0%	+0.1%	+0.1%	+0.4%	+1.5%

Table A2.5. Thermal and fast reactor fission rate spectrum-averaged values

	^{235}U thermal	^{235}U fast	^{238}U fast	^{239}Pu thermal	^{239}Pu fast
JEF-2.2	0.01654 ±3.0%	0.01658 ±3.0%	0.0468 ±6.5%	0.00647 ±4.0%	0.00646 ±4.0%
Change	-2%	+0.0%	+0.1%	+0.4%	+1.5%
Adjusted	0.01621 ±1.3%	0.01658 ±1.6%	0.0469 ±2.4%	0.00650 ±1.7%	0.00656 ±2.6%
Uncertainties proposed by Fort, *et al*.	±1.8%	±1.9%	±4.0%	±2.2%	±2.1%

These results indicating the percentage changes and adjusted values are listed in Table A2.5.

These spectrum-averaged values depend on the assumed fission rate spectrum for the reactor. For the systems studied by Fort, Zammit-Averlant, *et al*. there is a variation about these JEF-2.2 values of about ±0.1% for ^{235}U and ^{239}Pu and a variation of about ±1% for ^{238}U. For the adjusted values the variation is larger because of the broad group structure used to calculate the adjustments. The associated uncertainty estimates are also approximate. In particular the uncertainties of the adjusted values have been calculated without the use of covariance matrices. We should also note that there could be additional sources of uncertainty which should be taken into account and the figures in the row entitled "Uncertainties proposed by Fort, *et al*." reflects their estimates of the effects of these additional sources of uncertainty. They have also used different weighting spectra and a different way of averaging the uncertainties.

We should note that the change to the ^{235}U yield values results in a significant change in the variation of the yield with energy, between thermal and the range 10 to 500 keV, a variation of +2.6%. For ^{239}Pu there is a change from a variation of -0.9% to +0.6%.

If we are justified in saying that changes of 0.5% or less are not significant then we can interpret the results as confirming the ^{238}U data in JEF-2.2 (and JENDL-3.2) and also confirming the ^{235}U fast spectrum data and the ^{239}Pu thermal spectrum data. The only changes which are indicated as significant are the reduction in the ^{235}U thermal value and the increase in the ^{239}Pu fast spectrum value.

The uncertainty estimates given in Table A2.5 associated with the adjusted values are the values corresponding to the five-group adjustments given in Table A2.2. As we have seen above Fort, *et al*. have in most cases increased these uncertainties to allow for other sources and these increased values are given in the bottom row of Table A2.5. An even higher value is given by them for the uncertainty in the ^{238}U yield in a thermal reactor spectrum, ±5.6% (compared with ±4.0% for the average yield in a fast reactor spectrum). (We note that some of the spectrum-averaged adjusted values given by Fort, *et al*. also differ from the values given in Table A2.5.)

Thermal spectrum-averaged values

The change which has been proposed by E. Fort, *et al*. to the ^{235}U thermal spectrum-averaged value is based on the measurements made in the SHE-8 [93] and the MISTRAL-1 [94] programmes (although some of the fast spectrum systems have a significant sensitivity to the energy range below 10 keV, which is treated as a single energy group, Group 1).

	Measured	s.d. %	Calculated	(E – C)/C %
SHE-8	696	4.6%	694.2	0.26%
MISTRAL-1	789.7	1.6%	808.2	-2.29%

The JEF-2.2 delayed neutron yield evaluation for ^{235}U was normalised at thermal energies to the value of beta recommended by Kaneko, *et al*. [93]. This value was based on an analysis of the SHE programme of measurements and had an estimated uncertainty of ±1.2%. It is not surprising, therefore, that calculation is in agreement with the value measured in SHE-8. The adjusted yield value depends on the relative weights given to the JEF-2.2 thermal value, (±3.0%), to the SHE-8 measurement, (±4.6%) and to the MISTRAL-1 measurement (±1.6%). This latter experiment has a much higher weight in the fit, resulting in the proposed reduction of 2% in the ^{235}U thermal value.

Confirmation of the need for a lower ^{235}U thermal value is given by the analysis made by Sakurai and Okajima [130]. They included in their study a measurement made in a uranium-fuelled thermal reactor core, built in TCA, together with the benchmark series of fast reactor spectrum systems (the MASURCA (BERENICE) cores and the FCA (XIX) cores). The analysis was made using the JENDL-3.2 nuclear data library. The thermal spectrum yield for ^{235}U in JENDL-3.2 is 0.01600, which is 3.3% lower than the value in JEF-2.2. Even so, the C/E value for the β_{eff} measurement in the TCA core is 1.024. In their adjustment study Sakurai and Okajima reduce both the ^{235}U yield (by 0.9%) and the ^{238}U yield (by 3.08%) resulting in a 1.2% improvement in the agreement. The resulting adjusted value of the yield for ^{235}U is 0.01586 (which is 2.2% lower than the adjusted value obtained by Fort, *et al*.).

The adjustments made to the JENDL-3.2 yield data have been constrained by the form of the data representation. The data are represented at thermal, 3.3 MeV, 6.9 MeV and 13.5 MeV with a linear dependence between these energy points. The adjustment study includes two uranium-fuelled fast spectrum systems, R2 and XIX-1, and the β_{eff} values for these systems will have their strongest dependence on the thermal value of the ^{235}U yield as a consequence of the adoption of this form of energy dependence. The resulting energy variation of the yield, the difference between the thermal and fast spectrum-averaged values, is, as a consequence, much smaller than that found in the study by Fort, *et al*.

The MISTRAL-2 measurement is the only one for a MOX system for which an analysis has been published and it has been included in the adjustment study carried out by Fort, *et al*. This also has a high estimated accuracy.

	Measured	s.d. %	Calculated	(E – C)/C %
MISTRAL-1	372.5	1.6%	370.7	0.49%

The adjusted thermal value for ^{239}Pu, 0.00650±1.7% obtained by Fort, *et al.* is based on this result. There is also a dependence on the yield value for ^{238}U which is only marginally changed (+0.1%) in the fit.

The thermal value for ^{239}Pu obtained in the adjustment study of Sakurai and Okajima is determined by the fast reactor systems included in the study. The thermal value for ^{239}Pu before adjustment is 0.00622±6.5% and after adjustment is 0.00638±3.6%, 1.8% lower than the value of 0.00650±1.7% obtained by Fort, *et al*. The results are essentially consistent.

Fast spectrum-averaged values – the MASURCA and FCA benchmark series of measurements

It is of interest to look at the results for the benchmark experiments as presented by Okajima, *et al*. [90].

Table A2.6. C/E values based on the β_{eff} values as summarised by Okajima, *et al*. [90]

	R2	ZONA2	XIX-1	XIX-2	XIX-3
<β_{eff}> (pcm)	721	349	742	364	251
s.d. (pcm)	±11	±6	±24	±9	±4
s.d.%	1.5%	1.7%	3.2%	2.5%	1.6%
Main contributions	75% ^{235}U, 25% ^{238}U	42% ^{238}U, 48% ^{239}Pu	94% ^{235}U	11% ^{235}U, 46% ^{238}U, 41% ^{239}Pu	9% ^{235}U, 11% ^{238}U, 77% ^{239}Pu
C/E values					
J3.2/J3.2	1.008	0.995	1.004	1.005	0.972
J3.2/(J3.2 mod.)	1.016	1.019	1.003	1.010	0.978
J3.2/ENDF/B-VI	1.021	0.972	1.033	0.985	0.992
E1/JEF-2.2	1.028	0.999	1.029		1.010
E1/ENDF/B-VI	1.011	0.966	1.035		1.001

The J3.2/(J3.2 mod.) calculated values are the ones used in the adjustment study carried out by Sakurai and Okajima. The calculations differ from the first set of values in the delayed neutron spectrum used (ENDF/B-VI data are used) and include a treatment of the heterogeneity of the MASURCA cores – a very small effect. They also use earlier values for the mean β_{eff} values measured in R2 and ZONA2 (716±16 and 343±7), before the revisions to the CEA measured values were made by Fort, *et al*.

The reaction rate calculations have been made using either a data set based on JENDL-3.2 (J3.2) or using ERALIB1 (E1). These have been combined with the delayed neutron yield data in JENDL-3.2, ENDF/B-VI or JEF-2.2. Comparing the J3.2/B-VI and the E1/B-VI results we see the effects of using a different cross section-set to calculate the reaction rates. The results are within about 1% of each other.

We recall the fast spectrum-averaged yield values for the data in JEF-2.2, ENDF/B-VI and JENDL-3.2:

	^{235}U fast	**^{238}U fast**	**^{239}Pu fast**
JEF-2.2	0.01658	0.0468*	0.00646
ENDF/B-VI	0.01667	0.0429	0.00644
JENDL-3.2	0.0161	0.0471*	0.00627

* *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 corresponds to the ^{238}U fission rate spectrum in the XIX cores.*

It can be seen that the agreement of the β_{eff} values is generally within about ±3% for the three different yield data sets. The ENDF/B-VI yields give larger β_{eff} values than the JENDL-3.2 yields except for the ZONA2 and XIX-2 cores. The larger values of the delayed neutron yields for ^{235}U and ^{239}Pu in the ENDF/B-VI are primarily responsible for this. On the other hand, in the ZONA2 and XIX-2 cores, the larger yield values of ^{238}U in JENDL-3.2 give larger β_{eff} values since the contribution of ^{238}U is about 45% in these cores. The C/E values obtained using the JEF-2.2 yield data are higher than for JENDL-3.2 because the yield values for ^{235}U and ^{239}Pu are larger in JEF-2.2.

The pattern of results suggests that reducing the ^{235}U yield in B-VI and JEF-2.2 and increasing the ^{238}U yield in ENDF/B-VI would result in an improved agreement. We note that the study by Fort, *et al.* has indicated that a small increase in the JEF-2.2 ^{235}U fast spectrum yield above 10 keV would improve the overall agreement, but this study used the measurements made in two additional series of cores (SNEAK and ZPR). It also used different values for some of the measurements made in the benchmark series (and, in particular, a higher "effective" value for the measurement in R2, when account is taken of the form of the covariance matrix) and the 0.4% increase above 10 keV could be a partial compensation for the 2% reduction below 10 keV.

Sakurai and Okajima [131] made their adjustment study based on their analysis of the MASURCA (BERENICE) and FCA (XIX) benchmark series of measurements (together with a uranium-fuelled thermal spectrum system studied in TCA). They adjusted the total yield data in the JENDL-3.2 library. The yield data are given at four energy points with linear interpolation between these points. Based on the adjusted data of Sakurai and Okajima we calculate the fast reactor spectrum-averaged adjusted values and percentage changes to the JENDL-3.2 values (see Table A2.7).

Table A2.7. Fast reactor fission rate spectrum-averaged values, based on the work of Sakurai and Okajima [130], compared with values based on the adjustments calculated by Fort, *et al*.

	^{235}U fast	**^{238}U fast**	**^{239}Pu fast**
JENDL-3.2	0.0161	0.0471	0.00627
Change	-0.8%	-3.1%	+2.4%
Adjusted	0.0160±1.8%	0.0456±3.6%	0.00642±3.6%
Fort, *et al*.	0.01658±1.6%	0.0469±2.4%	0.00656±2.6%
Difference (%)	3.6%	2.9%	2.2%

The values are approximate because of the assumptions made about the choice of fast reactor fission rate spectrum used to derive the spectrum-averaged values. This could affect the values for ^{235}*U and* ^{239}*Pu by about 0.1% and for* ^{238}*U by about 1%. The uncertainty estimates are also approximate. The covariance matrices of the adjusted values have also been calculated by Sakurai and Okajima and these should be used to calculate the uncertainty in a* β_{eff} *calculation.*

We note that the values corresponding to the adjusted data of Sakurai and Okajima are lower than those corresponding to the adjusted data of Fort, *et al*. The reasons for these differences lie in the differences in the treatment of the benchmark results, the assessment of uncertainties in the results and the inclusion of the SNEAK and ZPR measurements in the study carried out by Fort, *et al*.

Even though the adjusted yield for ^{238}U obtained by Sakurai and Okajima is a reduction of about 3% relative to JENDL-3.2 (and JEF-2.2) the adjusted value is about 6.3% higher than the ENDF/B-VI yield value.

The SNEAK and ZPR series of measurements

The additional uranium-fuelled cores included in the studies by Fort, *et al.* are given in the Table A2.8 together with the two benchmark experiments (using the average of the measured values calculated by Okajima, *et al.*).

We see that for these uranium-fuelled cores there is a very good agreement for both the JEF-2.2 and ENDF/B-VI calculated values. The lower yield value for ^{238}U in ENDF/B-VI gives the somewhat lower value for ^{239}U. The values of C/E for the two benchmark experiments, R2 and XIX-1, are higher than for the earlier measurements in SNEAK and ZPR, implying lower measured values of β_{eff} in the benchmark cores. Note, however, that the mean measured value for R2 calculated by Fort, *et al.* (using a different method to derive the individual measured values and uncertainties) is 2.6% higher.

The fast spectrum-averaged yield for ^{235}U is 2.9% lower in JENDL-3.2 than in JEF-2.2. The further reduction proposed in the JENDL-3.2 adjustment study is probably a consequence of the inclusion of the thermal spectrum measurement. There is no evidence from the fast spectrum measurements of a need to reduce the value by 0.8% (noting also that this adjustment study indicates a 3.1% decrease in the ^{238}U yield value). Similarly there is no evidence from these results for an increase in the JEF-2.2 yield value for ^{235}U. In fact the FCA XIX-1 measurement would be more consistent with a reduction in the JEF-2.2 value. However, the standard deviation is larger than the deviation in this case. There is no evidence to suggest that the discrepancies are energy dependent (other than the difference between the fast and thermal spectrum averages).

There are some significant differences between the values of β_{eff} measured by the different groups participating in the benchmark experiments, and this could indicate that the uncertainties on individual measurements should be increased. This would affect the relative weighting given to the benchmark experiments and the measurements made in the ZPR and SNEAK cores because only one measurement was made in each of those experiments.

For the additional plutonium-fuelled core, ZPR PuCSS, there is also a good agreement for the JEF-2.2 and ENDF/B-VI yields. Again there is a tendency for the benchmark C/E value to be higher than for the ZPR measurement, and thus for the β_{eff} value measured in the benchmark core to be smaller.

Table A2.8. Uranium-fuelled cores included in the studies by Fort, *et al*., and two benchmark experiments

Core	**Relative contributions to β_{eff}**	**Measurement s.d. (%)**	**E1/JEF-2.2 C/E values**	**E1/B-VI C/E values**	**Fort, *et al.* C/E values**	**J32/J32 C/E values**
ZPR U9	46% ^{235}U, 54% ^{238}U	2.1%	0.992	0.975	0.992	
SNEAK 9C1	72% ^{235}U, 28% ^{238}U	4.2%	1.001	0.981	1.001	
Benchmark R2	75% ^{235}U, 25% ^{238}U	1.5%	1.028	1.011	1.001*	1.008
Benchmark XIX-1	95% ^{235}U	3.2%	1.029	1.035	1.029	0.995
ZPR UFe Ref	99.7% ^{235}U, 0.3% ^{238}U	2.1%	1.005	1.011	1.005	
ZPR UFe Leak	99.7% ^{235}U, 0.3% ^{238}U	2.1%	0.998	1.004	0.998	

Core	Relative contributions to β_{eff}	Measurement s.d.(%)	E1/JEF-2.2 C/E values	E1/B-VI C/E values
ZPR PuCSS	98% ^{239}Pu	2.3%	0.993	0.989
Benchmark XIX-3	9% ^{235}U 11% ^{238}U 77% ^{239}Pu		1.010	1.001

For the mixed plutonium-uranium-fuelled cores the E1/JEF-2.2 and E1/ENDF/B-VI results are as follows:

Core	Relative contributions to β_{eff}	Measurement s.d.(%)	E1/JEF-2.2 C/E values	E1/B-VI C/E values
SNEAK 7A	8% ^{235}U, 51% ^{238}U, 39% ^{239}Pu	2.8%	0.981	0.947
SNEAK 7B	11% ^{235}U, 59% ^{238}U, 28% ^{239}Pu	2.8%	1.020	0.977
SNEAK 9C2	13% ^{235}U,49% ^{238}U, 36% ^{239}Pu	4.6%	0.959	0.923
ZPR CRef	2% ^{235}U, 59% ^{238}U, 36% ^{239}Pu9	2.2%	0.993	0.953
ZPR RSR	1% ^{235}U, 45% ^{238}U, 50% ^{239}Pu	2.2%	0.974	0.944
Benchmark ZONA2	2% ^{235}U, 42% ^{238}U, 48% ^{239}Pu	1.7%	0.999	0.966
Benchmark XIX-2	11% ^{235}U, 46% ^{238}U, 41% ^{239}Pu	2.5%		0.985*

** This C/E value for XIX-2 is the JENDL-3.2/ENDF/B-VI value.*

There is again a good agreement for the JEF-2.2 yield data, whereas there is strong evidence that the ^{238}U yield in ENDF/B-VI is too low. It is probably the measurements made in these SNEAK and ZPR cores which have resulted in the higher value for the yield in ^{238}U calculated by Fort, *et al.* and the increase in the yield for ^{239}Pu. Again there is a tendency for the C/E values for the benchmark measurements, ZONA2 and XIX-2, to be higher than those for the SNEAK and ZPR measurements, and hence for the values of β_{eff} measured for the benchmark cores to be lower.

Conclusions and recommendations

The JEF-2.2 total delayed neutron yield data give satisfactory results, there being no strong indication of a need to change them. It is considered that the proposed target accuracy of ±3% will be obtained in β_{eff} calculations made using these total delayed neutron data in JEF-2.2 provided that the relative fission rate and fission rate distribution calculations are not introducing a significant error. The JENDL-3.2 calculated β_{eff} values are also in good agreement with the measurements (to within about ±3%) for the systems studied (the benchmark series and the TCA core) and again there is very little gain from the proposed adjustments. However, the JENDL-3.2 analysis did not include the SNEAK and ZPR systems which are indicating the need to revise the ENDF/B-VI values.

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 resulted in smaller yield values than the study by Fort, *et al.* which 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 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 is suggested. It is considered that using these averaged values the target accuracy of ±3% (1 s.d.) will be achieved in β_{eff} calculations, and for fast spectrum systems the accuracy is expected to be better than this, perhaps ±2% (1 s.d.). Uncertainties due to relative fission rate and fission rate distribution calculations and calculations of the relative importances of delayed neutrons could add to these uncertainties but we note that there is agreement to within about 1% for β_{eff} calculations made using ERALIB-1 and JENDL-3.2 cross-section data).

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 (when account is taken of possible uncertainties in the energy spectra of delayed neutrons and in the calculations of relative fission rates). For the two plutonium-fuelled cores which contain no uranium or have a relatively low uranium content (ZPR PuCSS and FCA XIX-3) the values calculated using the ENDF/B-VI yields are in satisfactory agreement with the measured values. This suggests that the low values calculated for the MOX-fuelled cores are a consequence of the lower yield for ^{238}U in ENDF/B-VI. In fact both adjustment studies, that by Fort, *et al.* and that by Sakurai and Okajima, 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). Based on the adjusted data of Fort, *et al.* and of Sakurai and Okajima we obtain the spectrum-averaged values 0.0469±2.4% and 0.0456±3.6%, respectively, the weighted-average value being 0.0465. This weighted average is chosen as the recommended value.

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. However the higher value derived by Kaneko, *et al*. [93] on the basis of the SHE programme of measurements 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. Taking an average of the adjusted values derived by Fort, *et al.* and by Sakurai and Okajima, together with a higher weighting for the value of Kaneko, *et al*. we get a yield of 0.0162 (which corresponds to the value of Fort, *et al*.).

We note that this reduction relative to the JEF-2.2 and ENDF/B-VI values is also consistent with the yield measurement made by Parish, *et al*. [4] 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 difference 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 by Sakurai and Okajima. The weighted average is 0.0163.

The β_{eff} measurement made in MISTRAL-2 engenders 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. Their value is 2.0% lower than the value obtained by Fort, *et al.* but is essentially consistent with value of 0.00650, which is chosen as the recommended value. We note, however, that there was a measurement made for a MOX-fuelled system in the TCA programme and it was reported that the measured value was in agreement with the JENDL-3.2 calculated value. The thermal yield value for ^{239}Pu in JENDL-3.2 (0.00622) is 4.3% lower than this recommended value of 0.00650 and this apparent discrepancy should be investigated.

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 weighted average value, 0.00651, is chosen as the recommended value.

In summary, the recommended values are as shown in Table A2.9.

Table A2.9. Summary of recommended values

^{235}U thermal	^{235}U fast	^{238}U fast	^{239}Pu thermal	^{239}Pu fast
0.0162	0.0163	0.0465	0.00650	0.00651

On the basis of these spectrum-averaged values energy-dependent data are proposed, suitable for inclusion in the nuclear data libraries. There are many ways that a corresponding set of energy-dependent data could be chosen and it must be recognised that the following recommendations are not unique ways of representing the data.

In the case of ^{238}U the JENDL-3.2 (=JEF-2.2) data have been chosen as the starting point values because these provided the better agreement with the integral measurements. A small adjustment has been made to the values in the threshold range, a reduction of 0.7% to the values at 10E-5 eV, 3.5 MeV and 7 MeV. The resulting values are as follows:

1.000000-5	4.780000-2	3.500000+6	4.780000-2
7.000000+6	3.570000-2	2.000000+7	1.880000-2

In the case of ^{235}U and ^{239}Pu the approach has been to assume a variation linear in energy below 1 MeV defined by values at 10E-5 eV, 200 keV (a point representative of the fast spectrum-averaged value) and 1 MeV. Since the JEF-2.2 evaluations of Fort, *et al*. are the most recent these have been adopted for the data above the 1 MeV point. However, a simplification of the data is considered justified because of the uncertainties in the values. The number of significant figures has been reduced to three and the number of energy points has also been reduced.

The proposed data for ^{235}U are as follows. Based on the thermal value (10E-5 eV) of 0.0162, the fast spectrum value (200 keV) of 0.0163, a value of 0.0164 at 1 MeV and the JEF-2.2 data at 3.9 MeV and above (simplified) we have:

1.000000-5	1.620000-2	2.000000+5	1.630000-2	1.000000+6	1.640000-2
3.900000+6	1.670000-2	5.700000+6	1.320000-2	6.000000+6	1.240000-2
7.000000+6	1.100000-2	1.000000+7	1.100000-2	1.200000+7	8.900000-3
2.000000+7	7.100000-3				

The value at 1 MeV has been chosen to give an energy dependence between thermal and 1 MeV which is more consistent with the Krick and Evens data, the variation being 1.2% between thermal and 1 MeV and 0.6% per MeV between 1 and 3.9 MeV (the Krick and Evans variation being 0.6% +/- 1.0% per MeV). The variation between thermal and 200 keV is the much larger value of 3% per MeV but this is affected by the number of significant figures used to represent the values.

The proposed data for ^{239}Pu are as follows. Based on the thermal value (10E-5 eV) of 0.00650, the fast spectrum value (200 keV) of 0.00651, a value at 1 MeV of 0.00661 and again with the JEF-2.2 data at 2.4 MeV and above (simplified) we have:

1.000000-5	6.500000-3	2.000000+5	6.510000-3	1.000000+6	6.610000-3
2.400000+6	6.690000-3	4.000000+6	6.550000-3	5.500000+6	5.140000-3
6.500000+6	3.900000-3	1.000000+7	3.780000-3	1.200000+7	3.000000-3
1.800000+7	3.000000-3	2.000000+7	2.800000-3		

The value at 1 MeV has been chosen to give a variation between 200 keV and 1 MeV more consistent with the Krick and Evans data (which gives a variation of 2%±0.5% per MeV). With the value 0.00661 at 1 MeV the energy variation is 1.9% per MeV from 200 keV to 1 MeV and 0.9% per MeV between 1 and 2.4 MeV, the variation being 1.2% per MeV between thermal and 2.4 MeV.

Interpolation is linear in energy.

APPENDIX 3

Recommended relative abundances and energy spectra for the eight time-group representation, evaluated by Joann Campbell and Gregory Spriggs

The recommendations are for the use of the eight-group parameters and associated energy spectra described in the Los Alamos reports by Campbell and Spriggs, LA-UR-98-1691 [121] and LA-UR-99-2988 [122] (documents No.3 and No. 4 on the CD-ROM) and summarised in LA-UR-99-4000 [123]. The energy spectra given there are in the 16-group Hansen-Roach structure, reproduced in Table A3.1. The spectra have been calculated for the 20 fissionable isotopes given in Ref. [121] and at the three energies, thermal, fast and high.

Table A3.1. The Hansen-Roach cross-section energy intervals

Group	Energy intervals
1	3-17 MeV
2	1.4-3.0 MeV
3	0.9-1.4 MeV
4	0.4-0.9 MeV
5	0.1-0.4 MeV
6	17-100 keV
7	3-17 keV
8	0.55-3 eV
9	100-550 eV
10	30-100 eV
11	10-30 eV
12	3-10 eV
13	1-3 eV
14	0.4-1 eV
15	0.1-0.4 eV
16	Thermal

The half-lives for the eight groups were chosen to be the weighted averages of the half-lives of the set of dominant precursors in each group. In the first three groups there is just one dominant precursor, ^{87}Br, ^{137}I and ^{88}Br, whereas in the remaining five groups there are three or four dominant precursors. The half-lives used are as follows: 55.6 s, 24.5 s, 16.3 s, 5.21 s, 2.37 s, 1.04 s, 0.424 s, 0.195 s. The relative abundances have been calculated from measured data which had been analysed into six groups (or fewer, depending on the time range of the measurements. The criteria used to select the measured data are described in LA-UR-98-1691. The measurements chosen for use in the derivation of the relative abundances are given in Table A3.2.

Table A3.2. List of the chosen experimentally measured delayed neutron sets

The number to the far left of each title line is the set identifier (see LA-UR-98-918) for that particular data set. A set identifier has been assigned to each data set to aid the user in locating that particular data set in this Appendix. To the right of each isotope name is a four-letter designator that indicates the incident neutron energy causing the fission. As explained in LA-UR-98-1691, four energy regimes have been defined: 1) the thermal energy regime ($E < 10^{-6}$ MeV); the fast energy regime ($10^{-6} < E < 5$ MeV); the transitional energy regime ($5 < E < 13$ MeV); and the high-energy regime ($E > 13$ MeV). (No recommendations are made in LA-UR-98-1691 for the transitional energy regime.)

1:	^{229}Th_ther:	Thermal spectrum, 5 groups, Gudkov, *et al*. (1989)
5:	^{232}Th_fast:	Fast spectrum, 6 groups, Keepin, *et al*. (1957)
28:	^{232}Th_high:	15 MeV, 5 groups, Maksyutenko, *et al*. (1958)
32:	^{231}Pa_fast:	Above Cd cut-off, 6 groups, Anoussis, *et al*. (1973)
33:	^{231}Pa_high:	14.8 MeV max., 4 groups, Brown, *et al*. (1971)
34:	^{232}U_ther:	Thermal spectrum, 5 groups, Waldo, *et al*. (1981)
37:	^{233}U_ther:	Thermal spectrum, 6 groups, Keepin, *et al*. (1957)
42:	^{233}U_fast:	Fast spectrum, 6 groups, Keepin, *et al*. (1957)
51:	^{233}U_high:	14.7 MeV, 6 groups, East, *et al*. (1970)
68:	^{235}U_ther:	Thermal spectrum, 6 groups, Keepin, *et al*. (1957)
88:	^{235}U_fast:	0.624 MeV, 8 groups, Piksaikin, *et al*. (1997)
108:	^{235}U_high:	14.7 MeV, 6 groups, East, *et al*. (1970)
115:	^{236}U_fast:	~Fission spectrum, 6 groups, Gudkov, *et al*. (1989)
118:	^{238}U_fast:	Fast spectrum, 6 groups, Keepin, *et al*. (1957)
148:	^{238}U_high:	14.7 MeV, 6 groups, East, *et al*. (1970)
190:	^{237}Np_fast:	3.745 MeV, 8 groups, Piksaikin, *et al*. (1997)
195:	^{238}Pu_ther:	Thermal spectrum, 6 groups, Waldo, *et al*. (1981)
196:	^{238}Pu_fast:	Fast spectrum, 5 groups, Benedetti, *et al*. (1982)
199:	^{239}Pu_ther:	Thermal spectrum, 6 groups, Keepin, *et al*. (1957)
207:	^{239}Pu_fast:	Fast spectrum, 6 groups, Besant, *et al*. (1977)
214:	^{239}Pu_high:	15 MeV, 6 groups, Maksyutenko (1963a)
224:	^{240}Pu_fast:	Fast spectrum, 6 groups, Keepin, *et al*. (1957)
227:	^{241}Pu_ther:	Thermal spectrum, 5 groups, Cox (1961)
230:	^{241}Pu_fast:	~Fission spectrum, 6 groups, Gudkov, *et al*. (1989)
231:	^{242}Pu_fast:	Fast spectrum, 6 groups, Waldo, *et al*. (1981)
233:	^{242}Pu_high:	14.7 MeV, 6 groups, East, *et al*. (1970)
234:	^{241}Am_ther:	Thermal spectrum, 5 groups, Waldo, *et al*. (1981)
237:	^{241}Am_fast:	~Fission spectrum, 6 groups, Gudkov, *et al*. (1989)
238:	^{242m}Am_ther:	Thermal spectrum, 6 groups, Waldo, *et al*. (1981)
241:	^{243}Am_fast:	Fast spectrum, 7 groups, Charlton, *et al*. (1998)
242:	^{245}Cm_ther:	Thermal spectrum, 6 groups, Waldo, *et al*. (1981)
243:	^{249}Cf_ther:	Thermal spectrum, 4 groups, Waldo, *et al*. (1981)
245:	^{252}Cf_spon:	Spontaneous fission, 4 groups, Chulick, *et al*. (1969)

The ENDF/B-VI library contains energy spectra for 243 precursors on a 10 keV grid. These have been combined to obtain spectra for the eight time groups using the P_n values, evaluated by Mann, *et al.* [125], and the ENDF/B-VI cumulative yields, evaluated by England and Rider [33]. For the neutron emitted by a particular precursor, the fractions of the spectrum contributing to the two adjacent groups of the eight-group structure were based on the half-life of the precursor and the half-lives of the two groups. The resulting spectra were then integrated over the energy groups of the Hansen and Roach 16-group structure. The average energy of the spectrum in each of the eight time groups has also been calculated.

The relative abundances and 16-group spectra are given in Table A3.3.

Table A3.3. Relative abundances and 16-group energy spectra

```
1: Th-229_ther: Thermal Spectrum, 5-groups, Gudkov et al. (1989)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    .113   +/- 1.10E-02
2 24.5  +/- .000    .250   +/- 2.30E-02
3 16.3  +/- .000    .124   +/- 1.40E-02
4 5.21  +/- .000    .242   +/- 1.90E-02
5 2.37  +/- .000    .178   +/- 1.60E-02
6 1.04  +/- .000    7.10E-02 +/- 1.40E-02
7  .424  +/- .000    2.23E-02 +/- 9.20E-03
T-mean = Sum[a(i)*T(i)]   = 16.19 s
T-mean = 1.0/Sum[a(i)/T(i)] = 3.81 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
 1 0.000 0.000 0.000 0.000 0.001 0.002 0.014 0.001
 2 0.000 0.012 0.002 0.016 0.059 0.063 0.081 0.024
 3 0.008 0.181 0.012 0.067 0.161 0.147 0.119 0.106
 4 0.120 0.505 0.205 0.446 0.398 0.351 0.339 0.377
 5 0.602 0.262 0.535 0.380 0.307 0.345 0.360 0.379
 6 0.238 0.038 0.204 0.081 0.066 0.084 0.076 0.101
 7 0.030 0.002 0.035 0.009 0.007 0.007 0.011 0.012
 8 0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.001
 9 0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 1.000 1.000 1.000 1.001 1.000
keV  211  600  256  473  596  575  635  481
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
5: Th-232_fast: Fast Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.34E-02 +/- 2.50E-03
2 24.5  +/- .000    7.32E-02 +/- 5.30E-03
3 16.3  +/- .000    9.30E-02 +/- 1.90E-03
4 5.21  +/- .000    .136   +/- 2.40E-02
5 2.37  +/- .000    .381   +/- 7.60E-03
6 1.04  +/- .000    .140   +/- 8.20E-03
7  .424  +/- .000    .114   +/- 1.30E-02
8  .195  +/- .000    2.81E-02 +/- 5.60E-04
T-mean = Sum[a(i)*T(i)]   = 6.98 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.34 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
 1 0.000 0.000 0.000 0.000 0.001 0.002 0.023 0.013 0.003
 2 0.000 0.012 0.003 0.016 0.064 0.061 0.088 0.072 0.048
 3 0.008 0.169 0.015 0.068 0.161 0.133 0.105 0.120 0.118
 4 0.120 0.489 0.214 0.429 0.383 0.340 0.315 0.336 0.357
 5 0.602 0.275 0.528 0.389 0.316 0.363 0.352 0.364 0.364
 6 0.238 0.050 0.199 0.086 0.066 0.091 0.099 0.085 0.093
 7 0.030 0.004 0.034 0.011 0.008 0.009 0.018 0.009 0.013
 8 0.001 0.001 0.006 0.002 0.001 0.001 0.001 0.000 0.002
 9 0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 1.001 1.000 1.000 1.001 0.999 0.999
keV  211  578  265  462  598  553  655  617  534
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
28: Th-232_high: 15 MeV, 5-groups, Maksyutenko et al. (1958)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.66E-02 +/- 4.10E-03
2 24.5  +/- .000    7.37E-02 +/- 7.50E-03
3 16.3  +/- .000    9.78E-02 +/- 1.50E-02
4 5.21  +/- .000     .209  +/- 1.60E-02
5 2.37  +/- .000     .262  +/- 3.90E-02
6 1.04  +/- .000     .219  +/- 2.30E-02
7  .424  +/- .000     .101  +/- 1.50E-02
T-mean = Sum[a(i)*T(i)]   = 7.42 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.64 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.001 0.002 0.021 0.003
2  0.000 0.012 0.003 0.015 0.067 0.064 0.085 0.045
3  0.008 0.182 0.016 0.067 0.176 0.151 0.122 0.121
4  0.120 0.509 0.216 0.423 0.395 0.367 0.343 0.370
5  0.602 0.259 0.528 0.395 0.294 0.338 0.341 0.361
6  0.238 0.035 0.197 0.087 0.061 0.072 0.076 0.088
7  0.030 0.002 0.033 0.011 0.006 0.006 0.012 0.011
8  0.001 0.000 0.006 0.002 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 1.000 1.001 1.001 1.000 0.999
keV  211  604  267  459  621  588  677  534
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
32: Pa-231_fast: Above Cd Cutoff, 6-groups, Anoussis et al. (1973)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    .115   +/- 6.60E-04
2 24.5  +/- .000    9.94E-02 +/- 2.20E-03
3 16.3  +/- .000    .228   +/- 6.00E-03
4  5.21  +/- .000    .181   +/- 2.60E-02
5  2.37  +/- .000    .353   +/- 3.00E-02
6  1.04  +/- .000    2.40E-02 +/- 1.00E-02
T-mean = Sum[a(i)*T(i)]   = 14.35 s
T-mean = 1.0/Sum[a(i)/T(i)] = 4.41 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.007 0.000
2  0.000 0.012 0.002 0.015 0.052 0.070 0.025
3  0.008 0.185 0.014 0.066 0.144 0.129 0.088
4  0.120 0.511 0.201 0.423 0.382 0.349 0.330
5  0.602 0.258 0.543 0.398 0.341 0.341 0.419
6  0.238 0.032 0.199 0.086 0.071 0.087 0.119
7  0.030 0.001 0.034 0.011 0.008 0.016 0.017
8  0.001 0.000 0.006 0.001 0.001 0.001 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 1.000 0.999 1.000 1.000
keV  211  608  259  457  564  590  440
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
33: Pa-231_high: 14.8 MeV max, 4-groups, Brown et al. (1971)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    .126   +/- 1.30E-02
2 24.5  +/- .000    6.84E-02 +/- 1.60E-02
3 16.3  +/- .000    .232   +/- 2.10E-02
4  5.21  +/- .000    .205   +/- 2.80E-02
5  2.37  +/- .000    .341   +/- 3.10E-02
6  1.04  +/- .000    2.76E-02 +/- 1.20E-02
T-mean = Sum[a(i)*T(i)]   = 14.37 s
T-mean = 1.0/Sum[a(i)/T(i)] = 4.37 s

DELAYED NEUTRON SPECTRA: (Used fission yields from Pa-231_fast)
DN Group Number-->
   1   2   3   4   5   6  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.007 0.000
2  0.000 0.012 0.002 0.015 0.052 0.070 0.024
3  0.008 0.185 0.014 0.066 0.144 0.129 0.083
4  0.120 0.511 0.201 0.423 0.382 0.349 0.323
5  0.602 0.258 0.543 0.398 0.341 0.341 0.427
6  0.238 0.032 0.199 0.086 0.071 0.087 0.123
7  0.030 0.001 0.034 0.011 0.008 0.016 0.017
8  0.001 0.000 0.006 0.001 0.001 0.001 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 1.000 0.999 1.000 1.000
keV  211  608  259  457  564  590  431
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
34: U-232__ther: Thermal Spectrum, 5-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    .109   +/- 8.70E-03
2 24.5  +/- .000    .144   +/- 1.50E-02
3 16.3  +/- .000    .178   +/- 1.90E-02
4  5.21  +/- .000    .218   +/- 3.30E-02
5  2.37  +/- .000    .270   +/- 5.40E-03
6  1.04  +/- .000    7.64E-02 +/- 4.80E-02
7  .424 +/- .000    4.60E-03 +/- 8.00E-02
T-mean = Sum[a(i)*T(i)]   = 14.35 s
T-mean = 1.0/Sum[a(i)/T(i)] = 3.86 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.013 0.000
2  0.000 0.012 0.002 0.016 0.041 0.052 0.076 0.021
3  0.008 0.185 0.012 0.065 0.119 0.127 0.095 0.086
4  0.120 0.510 0.198 0.436 0.378 0.355 0.344 0.347
5  0.602 0.259 0.547 0.394 0.375 0.380 0.341 0.418
6  0.238 0.033 0.199 0.080 0.077 0.078 0.099 0.111
7  0.030 0.001 0.034 0.008 0.009 0.006 0.032 0.014
8  0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 0.999 1.000 1.000 1.000 1.001 1.000
keV  211  608  256  465  524  541  593  443
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
37: U-233__ther: Thermal Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    7.97E-02 +/- 3.60E-03
2 24.5  +/- .000    .167   +/- 3.50E-03
3 16.3  +/- .000    .150   +/- 3.00E-03
4  5.21  +/- .000    .200   +/- 4.00E-02
5  2.37  +/- .000    .298   +/- 2.20E-02
6  1.04  +/- .000    3.88E-02 +/- 7.80E-04
7  .424 +/- .000    5.60E-02 +/- 2.50E-02
8  .195 +/- .000    1.05E-02 +/- 2.10E-04
T-mean = Sum[a(i)*T(i)]   = 12.78 s
T-mean = 1.0/Sum[a(i)/T(i)] = 2.47 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.016 0.012 0.001
2  0.000 0.012 0.003 0.015 0.048 0.055 0.081 0.067 0.027
3  0.008 0.184 0.014 0.064 0.132 0.130 0.098 0.113 0.097
4  0.120 0.511 0.212 0.414 0.374 0.350 0.344 0.330 0.357
5  0.602 0.258 0.531 0.407 0.362 0.372 0.337 0.370 0.397
6  0.238 0.033 0.199 0.087 0.074 0.084 0.093 0.094 0.104
7  0.030 0.001 0.034 0.011 0.009 0.007 0.029 0.013 0.015
8  0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.000 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 0.999 1.000 1.000 0.999 0.999 1.000
keV  211  607  263  450  543  545  621  590  472
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
42: U-233__fast: Fast Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    8.03E-02 +/- 6.10E-03
2 24.5  +/- .000    .157   +/- 2.90E-03
3 16.3  +/- .000    .135   +/- 2.70E-03
4  5.21  +/- .000    .209   +/- 3.70E-02
5  2.37  +/- .000    .308   +/- 6.20E-03
6  1.04  +/- .000    3.68E-02 +/- 7.40E-04
7  .424 +/- .000    6.17E-02 +/- 8.60E-03
8  .195 +/- .000    1.28E-02 +/- 1.10E-02
T-mean = Sum[a(i)*T(i)]   = 12.40 s
T-mean = 1.0/Sum[a(i)/T(i)] = 2.31 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.014 0.010 0.001
2  0.000 0.012 0.002 0.016 0.045 0.053 0.080 0.060 0.027
3  0.008 0.184 0.013 0.065 0.125 0.127 0.097 0.096 0.095
4  0.120 0.509 0.206 0.427 0.373 0.346 0.350 0.318 0.360
5  0.602 0.259 0.538 0.399 0.370 0.379 0.332 0.389 0.398
6  0.238 0.034 0.200 0.083 0.077 0.086 0.094 0.108 0.103
7  0.030 0.001 0.034 0.009 0.009 0.007 0.032 0.019 0.014
8  0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.001 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 1.000 1.000 1.000 1.000 1.001 1.001
keV  211  606  260  460  532  537  608  547  472
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
51: U-233__high: 14.7 MeV, 6-groups, East et al. (1970)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    9.25E-02 +/- 2.20E-03
2 24.5  +/- .000    7.83E-02 +/- 1.60E-03
3 16.3  +/- .000    .140   +/- 2.50E-03
4  5.21  +/- .000    .204   +/- 1.80E-02
5  2.37  +/- .000    .330   +/- 7.50E-03
6  1.04  +/- .000    5.76E-02 +/- 9.40E-03
7  .424 +/- .000    7.16E-02 +/- 1.40E-03
8  .195 +/- .000    2.60E-02 +/- 1.60E-03
T-mean = Sum[a(i)*T(i)]   = 11.28 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.82 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.021 0.012 0.002
2  0.000 0.012 0.002 0.016 0.048 0.052 0.082 0.061 0.031
3  0.008 0.181 0.013 0.065 0.137 0.131 0.100 0.101 0.093
4  0.120 0.504 0.196 0.425 0.380 0.359 0.349 0.316 0.344
5  0.602 0.264 0.550 0.400 0.354 0.376 0.337 0.392 0.408
6  0.238 0.036 0.198 0.083 0.072 0.075 0.084 0.104 0.106
7  0.030 0.002 0.034 0.009 0.008 0.005 0.026 0.014 0.015
8  0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.000 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 0.999 1.000 1.000 1.000 1.000 1.000
keV  211  601  257  459  552  547  648  563  471
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
68: U-235__ther: Thermal Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.28E-02 +/- 4.20E-03
2 24.5  +/- .000     .154   +/- 6.80E-03
3 16.3  +/- .000    9.14E-02 +/- 9.00E-03
4  5.21  +/- .000     .197   +/- 2.30E-02
5  2.37  +/- .000     .331   +/- 6.60E-03
6  1.04  +/- .000    9.03E-02 +/- 4.50E-03
7  .424 +/- .000    8.12E-02 +/- 1.60E-03
8  .195 +/- .000    2.29E-02 +/- 9.50E-03
T-mean = Sum[a(i)*T(i)]   = 9.03 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.71 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.002 0.016 0.008 0.002
2  0.000 0.013 0.003 0.014 0.044 0.048 0.078 0.077 0.032
3  0.008 0.186 0.016 0.064 0.117 0.110 0.100 0.133 0.103
4  0.120 0.515 0.222 0.401 0.358 0.335 0.340 0.345 0.367
5  0.602 0.254 0.522 0.415 0.388 0.403 0.350 0.348 0.390
6  0.238 0.031 0.197 0.092 0.080 0.092 0.092 0.078 0.093
7  0.030 0.001 0.033 0.012 0.011 0.008 0.023 0.009 0.013
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 1.000 0.999 0.999 1.000 0.998 1.001
keV  211  612  269  441  516  512  616  619  494
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
88: U-235__fast: 0.624 MeV, 8-groups, Piksaikin et al. (1997)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.40E-02 +/- 7.00E-04
2 24.5  +/- .000    .150   +/- 3.00E-03
3 16.3  +/- .000    9.91E-02 +/- 3.00E-03
4  5.21  +/- .000    .200   +/- 4.00E-03
5  2.37  +/- .000    .312   +/- 7.00E-03
6  1.04  +/- .000    9.31E-02 +/- 4.00E-03
7  .424 +/- .000    8.71E-02 +/- 4.00E-03
8  .195 +/- .000    2.40E-02 +/- 1.00E-03
T-mean = Sum[a(i)*T(i)]   = 9.10 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.66 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.014 0.008 0.002
2  0.000 0.012 0.003 0.015 0.050 0.056 0.078 0.066 0.034
3  0.008 0.185 0.015 0.066 0.130 0.123 0.096 0.114 0.106
4  0.120 0.512 0.213 0.416 0.364 0.336 0.341 0.328 0.368
5  0.602 0.257 0.531 0.403 0.368 0.384 0.340 0.375 0.381
6  0.238 0.033 0.197 0.087 0.076 0.090 0.099 0.096 0.093
7  0.030 0.001 0.034 0.011 0.010 0.008 0.030 0.013 0.013
8  0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 0.999 0.999 0.999 0.999 1.000 0.999
keV  211  609  265  453  542  534  603  572  501
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
108: U-235__high: 14.7 MeV, 6-groups, East et al. (1970)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    5.20E-02 +/- 1.00E-03
2 24.5  +/- .000    9.91E-02 +/- 2.00E-03
3 16.3  +/- .000    .107   +/- 4.10E-03
4  5.21  +/- .000    .185   +/- 2.20E-02
5  2.37  +/- .000    .346   +/- 6.90E-03
6  1.04  +/- .000    7.92E-02 +/- 8.60E-03
7  .424 +/- .000    8.73E-02 +/- 1.80E-03
8  .195 +/- .000    4.51E-02 +/- 8.30E-03
T-mean = Sum[a(i)*T(i)]   = 8.98 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.42 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.023 0.013 0.003
2  0.000 0.012 0.002 0.016 0.051 0.054 0.086 0.062 0.037
3  0.008 0.183 0.013 0.067 0.140 0.131 0.104 0.105 0.105
4  0.120 0.507 0.199 0.434 0.378 0.356 0.346 0.318 0.362
5  0.602 0.261 0.547 0.391 0.350 0.374 0.335 0.389 0.385
6  0.238 0.034 0.199 0.081 0.071 0.077 0.081 0.100 0.094
7  0.030 0.002 0.034 0.009 0.008 0.006 0.023 0.013 0.013
8  0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.001 0.999 0.999 1.000 0.999 1.000 1.001
keV  211  604  257  467  558  549  669  574  506
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
115: U-236__fast: ~Fission Spectrum, 6-groups, Gudkov et al.
(1989)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    2.45E-02 +/- 4.10E-03
2 24.5  +/- .000    9.80E-02 +/- 1.80E-02
3 16.3  +/- .000    .108   +/- 2.30E-02
4  5.21  +/- .000    .127   +/- 2.60E-02
5  2.37  +/- .000    .410   +/- 7.50E-02
6  1.04  +/- .000    .137   +/- 3.50E-02
7  .424 +/- .000    8.75E-02 +/- 1.70E-02
8  .195 +/- .000    8.30E-03 +/- 1.00E-02
T-mean = Sum[a(i)*T(i)]   = 7.34 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.70 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.002 0.021 0.011 0.002
2  0.000 0.013 0.003 0.014 0.046 0.050 0.083 0.057 0.037
3  0.008 0.186 0.018 0.064 0.121 0.112 0.095 0.098 0.102
4  0.120 0.516 0.239 0.401 0.357 0.331 0.332 0.315 0.354
5  0.602 0.253 0.501 0.413 0.383 0.401 0.344 0.399 0.391
6  0.238 0.032 0.199 0.093 0.080 0.095 0.098 0.106 0.097
7  0.030 0.001 0.033 0.012 0.011 0.009 0.027 0.014 0.014
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 1.000 0.999 0.999 1.001 1.001 1.000 1.000
keV  211  612  276  441  524  513  634  550  496
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
118: U-238__fast: Fast Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    8.40E-03 +/- 1.30E-03
2 24.5  +/- .000     .104   +/- 2.20E-03
3 16.3  +/- .000    3.75E-02 +/- 7.50E-04
4  5.21  +/- .000     .137   +/- 2.00E-02
5  2.37  +/- .000     .294   +/- 1.20E-02
6  1.04  +/- .000     .198   +/- 2.30E-03
7  .424 +/- .000    .128   +/- 1.30E-02
8  .195 +/- .000    9.31E-02 +/- 3.40E-03
T-mean = Sum[a(i)*T(i)]   = 5.32 s
T-mean = 1.0/Sum[a(i)/T(i)] = 0.89 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.001 0.002 0.030 0.014 0.006
2  0.000 0.013 0.004 0.014 0.053 0.051 0.085 0.060 0.046
3  0.008 0.187 0.022 0.064 0.128 0.111 0.095 0.102 0.110
4  0.120 0.517 0.261 0.390 0.353 0.332 0.312 0.307 0.356
5  0.602 0.251 0.478 0.420 0.374 0.399 0.362 0.406 0.380
6  0.238 0.031 0.196 0.097 0.078 0.095 0.098 0.101 0.090
7  0.030 0.001 0.033 0.013 0.011 0.009 0.017 0.009 0.012
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.001 1.000 0.999 1.000 1.000 0.999 1.000
keV  211  613  289  433  539  515  671  569  535
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
148: U-238__high: 14.7 MeV, 6-groups, East et al. (1970)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.60E-02 +/- 5.90E-04
2 24.5  +/- .000    8.92E-02 +/- 1.80E-03
3 16.3  +/- .000    5.10E-02 +/- 3.10E-03
4  5.21  +/- .000    .141   +/- 3.70E-03
5  2.37  +/- .000    .325   +/- 6.50E-03
6  1.04  +/- .000    .151   +/- 3.00E-03
7  .424 +/- .000    .121   +/- 2.40E-03
8  .195 +/- .000    .105   +/- 4.00E-03
T-mean = Sum[a(i)*T(i)]   = 5.64 s
T-mean = 1.0/Sum[a(i)/T(i)] = 0.88 s

DELAYED NEUTRON SPECTRA:.DN Group Number-->
   1    2    3    4    5    6    7    8   Comb.
1   0.000 0.000 0.000 0.000 0.000 0.002 0.027 0.012 0.005
2   0.000 0.013 0.004 0.014 0.048 0.047 0.084 0.057 0.042
3   0.008 0.187 0.021 0.065 0.126 0.107 0.098 0.102 0.107
4   0.120 0.516 0.235 0.392 0.360 0.334 0.327 0.317 0.356
5   0.602 0.253 0.510 0.418 0.376 0.409 0.351 0.399 0.385
6   0.238 0.031 0.190 0.096 0.078 0.093 0.091 0.102 0.091
7   0.030 0.001 0.032 0.013 0.010 0.008 0.020 0.011 0.012
8   0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9   0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 0.999 1.000 0.999 1.001 0.999 1.000 0.999
keV  211   613   282   436   532   505   668   560   523
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
190: Np-237_fast: 3.745 MeV, 8-groups, Piksaikin et al. (1997)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.47E-02 +/- 6.00E-04
2 24.5  +/- .000    .149   +/- 2.80E-03
3 16.3  +/- .000    8.93E-02 +/- 2.10E-03
4  5.21  +/- .000    .167   +/- 3.10E-03
5  2.37  +/- .000    .373   +/- 4.30E-03
6  1.04  +/- .000    2.07E-02 +/- 5.80E-04
7  .424 +/- .000    .141   +/- 4.00E-03
8  .195 +/- .000    2.54E-02 +/- 8.00E-04
T-mean = Sum[a(i)*T(i)]   = 8.88 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.46 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.020 0.012 0.003
2  0.000 0.013 0.003 0.014 0.042 0.049 0.083 0.058 0.034
3  0.008 0.186 0.018 0.063 0.116 0.112 0.094 0.095 0.102
4  0.120 0.515 0.226 0.389 0.355 0.333 0.339 0.308 0.361
5  0.602 0.254 0.519 0.423 0.393 0.402 0.337 0.400 0.388
6  0.238 0.031 0.194 0.095 0.081 0.093 0.096 0.110 0.095
7  0.030 0.001 0.033 0.013 0.010 0.008 0.030 0.016 0.015
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 0.999 0.998 0.999 1.000 0.999 1.000
keV  211  612  274  434  513  513  631  547  500
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
195: Pu-238_ther: Thermal Spectrum, 6-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    4.16E-02 +/- 9.20E-03
2 24.5  +/- .000    .219   +/- 2.70E-02
3 16.3  +/- .000    .137   +/- 5.80E-02
4  5.21  +/- .000    .134   +/- 6.50E-02
5  2.37  +/- .000    .386   +/- 7.70E-03
6  1.04  +/- .000    6.57E-02 +/- .100
7  .424 +/- .000    1.67E-02 +/- .170
T-mean = Sum[a(i)*T(i)]   = 11.60 s
T-mean = 1.0/Sum[a(i)/T(i)] = 3.23 s

DELAYED NEUTRON SPECTRA: (Used fission yields from Pu-238_fast)
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.013 0.001
2  0.000 0.013 0.003 0.014 0.035 0.041 0.068 0.023
3  0.008 0.186 0.017 0.063 0.106 0.103 0.092 0.105
4  0.120 0.515 0.232 0.394 0.353 0.339 0.336 0.385
5  0.602 0.253 0.510 0.423 0.410 0.418 0.362 0.387
6  0.238 0.031 0.197 0.092 0.084 0.090 0.101 0.087
7  0.030 0.001 0.033 0.012 0.010 0.007 0.027 0.010
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 0.999 1.000 0.999 1.000 1.000 0.999
keV  211  612  274  437  491  493  575  486
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
196: Pu-238_fast: Fast Spectrum, 5-groups, Benedetti et al. (1982)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    4.46E-02 +/- 8.20E-03
2 24.5  +/- .000     .250   +/- 1.80E-02
3 16.3  +/- .000    5.17E-02 +/- 1.00E-03
4  5.21  +/- .000     .256   +/- 1.40E-02
5  2.37  +/- .000     .251   +/- 3.50E-02
6  1.04  +/- .000     .119   +/- 1.20E-02
7  .424 +/- .000    2.69E-02 +/- 1.60E-02
T-mean = Sum[a(i)*T(i)]   = 11.51 s
T-mean = 1.0/Sum[a(i)/T(i)] = 2.88 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.013 0.001
2  0.000 0.013 0.003 0.014 0.035 0.041 0.068 0.023
3  0.008 0.186 0.017 0.063 0.106 0.103 0.092 0.105
4  0.120 0.515 0.232 0.394 0.353 0.339 0.336 0.385
5  0.602 0.253 0.510 0.423 0.410 0.418 0.362 0.387
6  0.238 0.031 0.197 0.092 0.084 0.090 0.101 0.087
7  0.030 0.001 0.033 0.012 0.010 0.007 0.027 0.010
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 0.999 1.000 0.999 1.000 1.000 0.999
keV  211  612  274  437  491  493  575  486
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
199: Pu-239_ther: Thermal Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.19E-02 +/- 1.20E-02
2 24.5  +/- .000     .237   +/- 3.40E-02
3 16.3  +/- .000    8.26E-02 +/- 1.60E-03
4  5.21  +/- .000     .182   +/- 5.20E-02
5  2.37  +/- .000     .294   +/- 2.90E-02
6  1.04  +/- .000    8.16E-02 +/- 1.60E-03
7  .424 +/- .000    7.22E-02 +/- 3.10E-02
8  .195 +/- .000    1.85E-02 +/- 3.70E-04
T-mean = Sum[a(i)*T(i)]   = 10.69 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.93 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1    2    3    4    5    6    7    8   Comb.
1   0.000 0.000 0.000 0.000 0.000 0.001 0.008 0.006 0.001
2   0.000 0.013 0.004 0.013 0.034 0.040 0.072 0.062 0.025
3   0.008 0.189 0.024 0.062 0.095 0.094 0.085 0.104 0.102
4   0.120 0.519 0.242 0.370 0.343 0.322 0.348 0.331 0.373
5   0.602 0.251 0.504 0.433 0.428 0.431 0.335 0.375 0.391
6   0.238 0.028 0.186 0.104 0.087 0.102 0.111 0.101 0.092
7   0.030 0.001 0.032 0.015 0.011 0.009 0.040 0.019 0.014
8   0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9   0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 0.999 0.999 0.999 1.000 1.000 0.998 1.000
keV  211   617   289   418   475   473   555   549   481
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
207: Pu-239_fast: Fast Spectrum, 6-groups, Besant et al. (1977)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    2.88E-02 +/- 2.10E-03
2 24.5  +/- .000     .225   +/- 4.50E-03
3 16.3  +/- .000    9.51E-02 +/- 9.80E-03
4  5.21  +/- .000     .149   +/- 4.30E-02
5  2.37  +/- .000     .351   +/- 7.00E-03
6  1.04  +/- .000    3.70E-02 +/- 1.90E-02
7  .424 +/- .000    9.74E-02 +/- 9.10E-02
8  .195 +/- .000    1.68E-02 +/- 3.90E-02
T-mean = Sum[a(i)*T(i)]   = 10.36 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.84 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.013 0.009 0.002
2  0.000 0.013 0.004 0.013 0.034 0.038 0.074 0.054 0.027
3  0.008 0.188 0.021 0.061 0.102 0.097 0.090 0.092 0.103
4  0.120 0.517 0.242 0.374 0.350 0.331 0.347 0.309 0.373
5  0.602 0.252 0.503 0.433 0.416 0.428 0.341 0.405 0.388
6  0.238 0.030 0.191 0.101 0.086 0.097 0.100 0.114 0.092
7  0.030 0.001 0.032 0.015 0.010 0.008 0.034 0.017 0.014
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 1.000 0.999 0.999 1.001 1.000 1.001 1.000
keV  211  615  284  421  484  477  586  523  488
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
214: Pu-239_high: 15 MeV, 6-groups, Maksyutenko (1963a)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    4.93E-02 +/- 8.20E-04
2 24.5  +/- .000    .145   +/- 2.90E-03
3 16.3  +/- .000    5.33E-02 +/- 4.10E-03
4  5.21  +/- .000    .212   +/- 7.10E-03
5  2.37  +/- .000    .312   +/- 6.20E-03
6  1.04  +/- .000    .121   +/- 4.80E-02
7  .424 +/- .000    .108   +/- .100
T-mean = Sum[a(i)*T(i)]   = 9.18 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.81 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1   0.000 0.000 0.000 0.000 0.000 0.001 0.017 0.002
2   0.000 0.012 0.002 0.016 0.049 0.050 0.075 0.035
3   0.008 0.183 0.012 0.065 0.139 0.128 0.102 0.111
4   0.120 0.508 0.198 0.428 0.378 0.359 0.337 0.379
5   0.602 0.260 0.547 0.401 0.353 0.380 0.353 0.376
6   0.238 0.034 0.200 0.081 0.072 0.077 0.092 0.086
7   0.030 0.002 0.034 0.008 0.007 0.005 0.022 0.011
8   0.001 0.000 0.006 0.001 0.001 0.001 0.001 0.001
9   0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 1.000 0.999 1.001 0.999 1.001
keV  211  605  256  462  553  539  618  514
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
224: Pu-240_fast: Fast Spectrum, 6-groups, Keepin et al. (1957)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    2.20E-02 +/- 3.30E-03
2 24.5  +/- .000    .207   +/- 4.80E-03
3 16.3  +/- .000    7.95E-02 +/- 1.60E-03
4  5.21  +/- .000    .161   +/- 5.50E-02
5  2.37  +/- .000    .314   +/- 8.80E-03
6  1.04  +/- .000    .105   +/- 9.80E-03
7  .424 +/- .000    7.93E-02 +/- 1.70E-02
8  .195 +/- .000    3.25E-02 +/- 3.00E-03
T-mean = Sum[a(i)*T(i)]   = 9.32 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.58 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.014 0.009 0.002
2  0.000 0.013 0.004 0.013 0.036 0.041 0.074 0.054 0.028
3  0.008 0.188 0.021 0.061 0.102 0.098 0.090 0.094 0.103
4  0.120 0.518 0.256 0.377 0.345 0.324 0.340 0.312 0.370
5  0.602 0.251 0.484 0.434 0.417 0.425 0.349 0.405 0.390
6  0.238 0.029 0.195 0.099 0.087 0.101 0.101 0.111 0.092
7  0.030 0.001 0.033 0.014 0.011 0.009 0.030 0.015 0.013
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 1.000 0.999 1.000 0.999 1.000 1.000
keV  211  615  287  423  485  480  591  529  490
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
227: Pu-241_ther: Thermal Spectrum, 5-groups, Cox (1961)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.09E-02 +/- 3.30E-03
2 24.5  +/- .000    .166   +/- 3.30E-03
3 16.3  +/- .000    9.45E-02 +/- 1.10E-02
4  5.21  +/- .000    .100   +/- 2.50E-02
5  2.37  +/- .000    .382   +/- 4.30E-02
6  1.04  +/- .000    7.34E-02 +/- 3.00E-02
7  .424 +/- .000    .174   +/- 1.20E-02
T-mean = Sum[a(i)*T(i)]   = 7.79 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.48 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.011 0.002
2  0.000 0.013 0.005 0.012 0.035 0.038 0.062 0.030
3  0.008 0.189 0.026 0.060 0.094 0.088 0.087 0.097
4  0.120 0.519 0.272 0.354 0.336 0.311 0.319 0.355
5  0.602 0.250 0.468 0.444 0.431 0.436 0.385 0.400
6  0.238 0.029 0.190 0.110 0.090 0.114 0.113 0.099
7  0.030 0.001 0.032 0.017 0.012 0.010 0.023 0.015
8  0.001 0.000 0.006 0.003 0.002 0.001 0.001 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 1.000 1.000 1.000 0.999 1.001 1.001
keV  211  617  299  406  470  457  542  481
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
230: Pu-241_fast: ~Fission Spectrum, 6-groups, Gudkov et al.
(1989)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.58E-02 +/- 2.20E-03
2 24.5  +/- .000    .175   +/- 1.90E-02
3 16.3  +/- .000    5.53E-02 +/- 1.20E-02
4  5.21  +/- .000    .170   +/- 1.80E-02
5  2.37  +/- .000    .280   +/- 3.50E-02
6  1.04  +/- .000    .166   +/- 3.30E-02
7  .424 +/- .000    .113   +/- 3.50E-02
8  .195 +/- .000    2.45E-02 +/- 6.30E-03
T-mean = Sum[a(i)*T(i)]   = 7.84 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.40 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.015 0.009 0.002
2  0.000 0.013 0.004 0.012 0.038 0.041 0.072 0.052 0.031
3  0.008 0.188 0.023 0.061 0.103 0.096 0.088 0.095 0.102
4  0.120 0.519 0.267 0.366 0.343 0.320 0.329 0.313 0.364
5  0.602 0.250 0.471 0.439 0.416 0.426 0.361 0.407 0.392
6  0.238 0.029 0.196 0.105 0.087 0.105 0.107 0.109 0.094
7  0.030 0.001 0.033 0.015 0.012 0.009 0.027 0.014 0.013
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.001 1.000 1.000 0.999 1.000 0.999 1.000
keV  211  616  292  415  486  476  584  529  492
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
231: Pu-242_fast: Fast Spectrum, 6-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.38E-02 +/- 2.80E-04
2 24.5  +/- .000    9.49E-02 +/- 5.10E-02
3 16.3  +/- .000    .134   +/- 1.50E-02
4  5.21  +/- .000    3.26E-02 +/- 2.00E-02
5  2.37  +/- .000    .404   +/- 8.10E-03
6  1.04  +/- .000    1.40E-03 +/- 6.00E-02
7  .424 +/- .000    .258   +/- 4.60E-02
8  .195 +/- .000    6.17E-02 +/- 5.20E-02
T-mean = Sum[a(i)*T(i)]   = 6.53 s
T-mean = 1.0/Sum[a(i)/T(i)] = 0.90 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.017 0.009 0.005
2  0.000 0.013 0.005 0.012 0.042 0.044 0.073 0.053 0.041
3  0.008 0.187 0.025 0.061 0.107 0.100 0.090 0.098 0.096
4  0.120 0.518 0.278 0.362 0.340 0.321 0.326 0.317 0.341
5  0.602 0.251 0.458 0.441 0.412 0.420 0.364 0.405 0.394
6  0.238 0.031 0.195 0.106 0.086 0.104 0.105 0.106 0.104
7  0.030 0.001 0.033 0.015 0.012 0.010 0.024 0.012 0.017
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 1.001 0.999 1.000 1.001 1.000 1.000 1.000
keV  211  614  297  412  495  485  596  536  502
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
233: Pu-242_high: 14.7 MeV, 6-groups, East et al. (1970)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    2.17E-02 +/- 4.60E-03
2 24.5  +/- .000    9.69E-02 +/- 1.90E-03
3 16.3  +/- .000    9.02E-02 +/- 1.80E-03
4  5.21  +/- .000    .108   +/- 1.80E-02
5  2.37  +/- .000    .366   +/- 3.70E-03
6  1.04  +/- .000    .111   +/- 2.20E-03
7  .424 +/- .000    .143   +/- 1.00E-02
8  .195 +/- .000    6.42E-02 +/- 6.30E-03
T-mean = Sum[a(i)*T(i)]   = 6.67 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.04 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.025 0.012 0.005
2  0.000 0.013 0.003 0.013 0.048 0.045 0.082 0.059 0.041
3  0.008 0.188 0.020 0.062 0.129 0.109 0.100 0.106 0.107
4  0.120 0.517 0.234 0.382 0.363 0.341 0.335 0.323 0.355
5  0.602 0.252 0.512 0.429 0.373 0.407 0.349 0.391 0.387
6  0.238 0.030 0.192 0.099 0.076 0.088 0.087 0.099 0.093
7  0.030 0.001 0.032 0.013 0.009 0.007 0.021 0.011 0.013
8  0.001 0.000 0.005 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 0.999 1.000 0.999 0.999 1.000 1.001 1.001
keV  211  615  279  427  535  508  661  568  519
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
234: Am-241_ther: Thermal Spectrum, 5-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.40E-02 +/- 3.10E-03
2 24.5  +/- .000     .238   +/- 3.30E-02
3 16.3  +/- .000    6.12E-02 +/- 1.20E-02
4  5.21  +/- .000     .182   +/- 3.30E-02
5  2.37  +/- .000     .305   +/- 3.50E-02
6  1.04  +/- .000     .106   +/- 2.10E-03
7  .424 +/- .000    3.84E-02 +/- 6.60E-02
8  .195 +/- .000    3.56E-02 +/- 7.20E-02
T-mean = Sum[a(i)*T(i)]   = 10.52 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.81 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.012 0.009 0.001
2  0.000 0.013 0.004 0.013 0.030 0.034 0.073 0.055 0.023
3  0.008 0.189 0.023 0.061 0.093 0.089 0.089 0.090 0.102
4  0.120 0.519 0.247 0.368 0.344 0.325 0.346 0.303 0.373
5  0.602 0.250 0.497 0.437 0.432 0.438 0.342 0.407 0.396
6  0.238 0.028 0.190 0.103 0.088 0.104 0.102 0.117 0.091
7  0.030 0.001 0.032 0.015 0.011 0.008 0.034 0.018 0.012
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 0.999 0.999 1.000 0.999 1.000 1.000
keV  211  617  288  417  466  461  580  521  480
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
237: Am-241_fast: ~Fission Spectrum, 6-groups, Gudkov et al.
(1989)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    3.90E-02 +/- 6.90E-03
2 24.5  +/- .000    .171   +/- 2.60E-02
3 16.3  +/- .000    .114   +/- 1.80E-02
4  5.21  +/- .000    .199   +/- 3.50E-02
5  2.37  +/- .000    .258   +/- 2.80E-02
6  1.04  +/- .000    8.48E-02 +/- 6.10E-02
7  .424 +/- .000    .114   +/- 8.80E-02
8  .195 +/- .000    2.17E-02 +/- 4.30E-04
T-mean = Sum[a(i)*T(i)]   = 10.01 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.60 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.013 0.009 0.002
2  0.000 0.013 0.003 0.013 0.032 0.036 0.072 0.056 0.026
3  0.008 0.188 0.017 0.062 0.100 0.095 0.089 0.089 0.093
4  0.120 0.517 0.222 0.381 0.350 0.329 0.346 0.300 0.358
5  0.602 0.252 0.522 0.429 0.421 0.430 0.348 0.409 0.405
6  0.238 0.029 0.195 0.098 0.086 0.100 0.099 0.118 0.101
7  0.030 0.001 0.033 0.013 0.010 0.007 0.032 0.018 0.015
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001 0.002
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 0.999 0.998 1.000 0.999 1.000 1.000 1.002
keV  211  616  272  427  478  471  583  524  471
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
238: Am-42m_ther: Thermal Spectrum, 6-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    2.10E-02 +/- 4.10E-04
2 24.5  +/- .000     .245   +/- 1.80E-02
3 16.3  +/- .000    6.04E-02 +/- 7.50E-03
4  5.21  +/- .000     .205   +/- 2.50E-02
5  2.37  +/- .000     .261   +/- 2.90E-02
6  1.04  +/- .000     .179   +/- 4.00E-02
7  .424 +/- .000    2.95E-02 +/- 5.60E-02
T-mean = Sum[a(i)*T(i)]   = 10.04 s
T-mean = 1.0/Sum[a(i)/T(i)] = 2.47 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.011 0.001
2  0.000 0.013 0.004 0.013 0.034 0.037 0.065 0.023
3  0.008 0.189 0.023 0.062 0.099 0.092 0.089 0.105
4  0.120 0.519 0.245 0.372 0.345 0.320 0.330 0.378
5  0.602 0.251 0.499 0.433 0.422 0.433 0.370 0.392
6  0.238 0.028 0.191 0.103 0.088 0.108 0.108 0.090
7  0.030 0.001 0.032 0.015 0.011 0.009 0.027 0.011
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.001 1.001 1.000 1.000 1.001 1.001 1.001
keV  211  617  286  420  477  463  553  483
```

```
241: Am-243_fast: Fast Spectrum, 7-groups, Charlton et al. (1998)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.77E-02 +/- 5.80E-03
2 24.5  +/- .000    .220   +/- 1.20E-02
3 16.3  +/- .000    9.80E-02 +/- 2.00E-03
4  5.21  +/- .000    .121   +/- 8.90E-03
5  2.37  +/- .000    .316   +/- 1.30E-02
6  1.04  +/- .000    .170   +/- 3.40E-03
7  .424 +/- .000    4.29E-02 +/- 1.10E-02
8  .195 +/- .000    1.49E-02 +/- 2.30E-03
T-mean = Sum[a(i)*T(i)]   = 9.55 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.95 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7   8  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.016 0.009 0.001
2  0.000 0.013 0.004 0.013 0.037 0.041 0.075 0.053 0.028
3  0.008 0.189 0.022 0.062 0.105 0.099 0.092 0.094 0.107
4  0.120 0.519 0.248 0.373 0.346 0.327 0.343 0.307 0.370
5  0.602 0.250 0.494 0.434 0.414 0.424 0.348 0.409 0.390
6  0.238 0.028 0.192 0.102 0.086 0.098 0.097 0.112 0.091
7  0.030 0.001 0.033 0.014 0.011 0.008 0.029 0.014 0.012
8  0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.000 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 1.000 1.000 1.000 1.000 0.999 1.001 0.998 1.000
keV  211  617  286  421  489  484  604  528  489
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
242: Cm-245_ther: Thermal Spectrum, 6-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.57E-02 +/- 4.30E-03
2 24.5  +/- .000     .269   +/- 2.00E-02
3 16.3  +/- .000    4.52E-02 +/- 9.00E-04
4  5.21  +/- .000     .204   +/- 4.60E-02
5  2.37  +/- .000     .255   +/- 4.00E-02
6  1.04  +/- .000     .178   +/- 5.00E-02
7  .424 +/- .000    3.34E-02 +/- 8.40E-02
T-mean = Sum[a(i)*T(i)]   = 10.07 s
T-mean = 1.0/Sum[a(i)/T(i)] = 2.43 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1   0.000 0.000 0.000 0.000 0.000 0.001 0.015 0.001
2   0.000 0.012 0.004 0.013 0.037 0.039 0.068 0.025
3   0.008 0.185 0.024 0.062 0.101 0.093 0.091 0.109
4   0.120 0.513 0.254 0.374 0.344 0.315 0.323 0.382
5   0.602 0.255 0.489 0.432 0.418 0.431 0.373 0.384
6   0.238 0.033 0.190 0.103 0.087 0.111 0.106 0.088
7   0.030 0.001 0.032 0.015 0.011 0.010 0.023 0.011
8   0.001 0.000 0.006 0.002 0.001 0.001 0.001 0.001
9   0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16  0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 0.999 0.999 1.000 1.001 0.999 1.001 1.000 1.000
keV  211  609  291  421  483  466  576  492
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
243: Cf-249_ther: Thermal Spectrum, 4-groups, Waldo et al. (1981)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    2.39E-02 +/- 4.80E-04
2 24.5  +/- .000    .292   +/- 2.30E-02
3 16.3  +/- .000    6.36E-02 +/- 1.10E-02
4  5.21  +/- .000    .228   +/- 2.80E-02
5  2.37  +/- .000    .265   +/- 2.60E-02
6  1.04  +/- .000    .127   +/- 1.70E-02
T-mean = Sum[a(i)*T(i)]   = 11.47 s
T-mean = 1.0/Sum[a(i)/T(i)] = 3.40 s

DELAYED NEUTRON SPECTRA: (No Fission Yield data was available)
```

Table A3.3. Relative abundances and 16-group energy spectra (*cont.*)

```
245: Cf-252_spon: Spontaneous Fission, 4-groups, Chulick et al.
(1969)
Half-lives +/- 1 sigma  Rel. Abun. +/- 1 sigma
1 55.6  +/- .000    1.43E-02 +/- 6.20E-03
2 24.5  +/- .000    .318   +/- 6.40E-03
3 16.3  +/- .000    1.40E-03 +/- 2.40E-02
4  5.21  +/- .000    .209   +/- 1.80E-02
5  2.37  +/- .000    .200   +/- 4.00E-03
6  1.04  +/- .000    .144   +/- 3.10E-02
7  .424 +/- .000    .112   +/- 4.40E-02
T-mean = Sum[a(i)*T(i)]   = 10.37 s
T-mean = 1.0/Sum[a(i)/T(i)] = 1.85 s

DELAYED NEUTRON SPECTRA:
DN Group Number-->
   1   2   3   4   5   6   7  Comb.
1  0.000 0.000 0.000 0.000 0.000 0.001 0.012 0.001
2  0.000 0.013 0.005 0.011 0.036 0.035 0.060 0.025
3  0.008 0.186 0.027 0.059 0.096 0.085 0.089 0.113
4  0.120 0.515 0.282 0.345 0.333 0.306 0.315 0.384
5  0.602 0.253 0.455 0.452 0.430 0.440 0.395 0.378
6  0.239 0.032 0.192 0.114 0.091 0.122 0.112 0.086
7  0.030 0.001 0.032 0.017 0.012 0.011 0.017 0.010
8  0.001 0.000 0.006 0.003 0.001 0.001 0.001 0.001
9  0.000 0.000 0.001 0.000 0.000 0.000 0.000 0.000
10 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
11 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
12 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
13 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
14 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
15 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
16 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
sum 1.000 1.000 1.000 1.001 0.999 1.001 1.001 0.999
keV  211  612  302  398  473  447  545  501
```

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