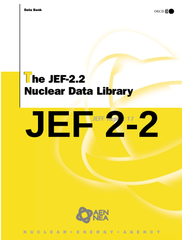
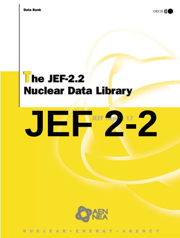


Chapter 10: Delayed Neutron Summation Calculations.

Introduction

The production of the JEF2.2 fission product yield evaluated files was described above. The confidence which can be held in the validity of this, or any other evaluated nuclear data file, depends upon the tests that are applied to the data. These tests can be of two types. The first type are tests of internal consistency which are based upon the intrinsic physics or the empirical data on which the evaluation is based. The second type, external tests, are where the data are used to model a phenomenon based upon a real situation and the results of these calculations are compared with experimental measurements.
The range of phenomena for which this second type of tests can be applied is as large as the range of applications for fission product yields. However these tests will inevitably involve a wide range of other nuclear data. For example to calculate the fission product inventory within a spent fuel rod it is necessary to know both initial composition of the rod, the rod's irradiation history and the relevant nuclear data (the actinide cross-sections, fission products yields, fission product cross-sections and half-lives of the materials present). Any discrepancy between calculation and measurement could result from each of the different types of nuclear data, or from the approximations inherent in the computer model and code used to calculate the inventory. It must also be remembered that the experimental measurements will have uncertainities. Also, parameters such as decay heat, photon and particle emission subsequently derived from the calculated inventory will thus be dependent both upon the many types of data used both to calculate the inventories and the data used to calculate the property in question such as half-lives, $P_{(}$, P_n, average energy per decay etc.
An important point to high-light for any testing is the consistency of all the files used. A simple example of data consistency would be the measurement of a fission yield by a characteristic gamma-ray emission. If the P_γ is over-estimated then the yield derived from the measurement will be under-estimated. However if this small yield is used with the large $P_{(}$ then a calculation of gamma emission will approximate to that measured experimentally. This is a case of correlation between the measured yield and the P_γ that cancels out when re-calculating the measured gamma emission.
An important example of consistency related to fission yield evaluation is the decay data set used within the evaluation procedure. If the decay data set used with the yields for inventory calculations has different P_n values from that used in the generation of the yield file then the internal consistency of the independent yields with the experimental chain yields will be lost and those long lived-fission products which have delayed neutron emitting precursors will be incorrectly calculated. This is even though these long-lived radio-nuclides are the most accurately measured.
Also, if the decay data set does not contain all the fission products in the yield set then the inventory calculations cannot estimate the spent fuel inventory correctly. The JEF2.2 fission product yield files were adjusted so that when used with the JEF2.2 decay data file they will reproduce the measured chain yields.

One type of calculation was chosen to test the evaluated fission yield data that only require the decay data to be known. This is the calculation of total delayed neutron emission. In this work very low values of neutron flux was assumed in the modelling so that cross-section effects could be ignored.



Delayed neutron calculations

If we consider delayed neutron emission from fission products, the governing phenomenon is the decay of a fission product that leaves a daughter nucleus with sufficient excitation energy to throw off a neutron. For nuclides where this occurs the fraction of decays that produce a neutron is called the P_n value; these nuclides are short-lived and on the neutron rich side of the line of stability.

The total number of delayed neutrons per fission, EMBED Paint.Picture , and the time dependence of the delayed neutron emission rate are important parameters for reactor design and safety studies, as they determine the kinetic response and behaviour of reactors. There exist three ways of determining EMBED Paint.Picture ; firstly experimentally from integral measurements e.g. Keepin , secondly from summation calculations e.g. Liaw et al using cumulative fission yields and P_n branching ratios; and thirdly by a more empirical method, proposed by Pai et al and modified by Tuttle , based upon systematics of the delayed neutron production with mass and charge of the fissioning compound nucleus.

The time dependence of delayed neutron emission can be determined by experiment or by summation calculations using the branching ratios, half-lives and inventories of the fission products following an irradiation e.g. the work of Brady and England . The proposed use of reprocessed fuel containing significant quantities of higher actinides has led to requests for the values of EMBED Paint.Pictur for these nuclides so that their effects on the kinetic response of reactors can be estimated for safety studies. As experiments with these materials are often difficult due to the lack of reasonably sized samples and thus reported experiments are rare in the literature, the summation method may be the most reliable way for these EMBED Paint.Picture 's to be estimated if it can be shown to be more accurate than the empirical extrapolation method of Pai[3] and Tuttle[4]. However the uncertainties in the yields and branching ratios of the delayed neutron emitters must be reviewed in order to decide whether the summation method is significantly accurate for practical use.

The delayed neutron emitters exist on the extremely neutron rich side of the independent fission yield distribution, where few fission product yield measurements have been made except for the more common actinides such as ^{235}U and ^{239}Pu. Thus the models used to predict the charge distribution of the fission yields will have a significant effect on EMBED Paint.Picture . Also the different chain yield distributions for the fission of the higher actinides mean that some precursors, relatively unimportant for ^{235}U fission, become much more significant. Especially important is the movement of the light mass peak towards higher mass as the mass of the fissioning nuclide increases. However, measurements of the P_n values have been based mainly upon ^{235}U fission so theoretical estimates of the P_n branching ratios become much more important when considering the higher actinides.

The neutron emission is a result of β^- decay producing a daughter which has sufficient energy to throw off a neutron. The probability of a nuclide emitting a neutron as a result of a β^- decay is referred to as the P_n.

The fission products present determine the delayed neutron emission rate, n_{emit}, from the activity of these precursors:

G.R.Keepin, Physics of Nuclear Kinetics, Addison-Wesley(1965).

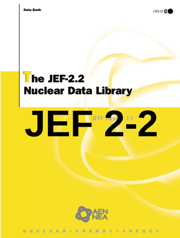
J.R.Liaw and T.R.England: Trans. Amer. Nucl. Soc. 28, 750 (1978).

H.L.Pai: Ann. Nucl. Energy, 3, 125(1976).

R.J.Tuttle in Proc. consultants' meeting on delayed neutrons properties, Vienna, 26-30 March(1979).

4a R.J. Tuttle, Nucl. Sci. Eng. 56, 37 (1975).

M.C.Brady and T.R.England: Nucl. Sci. Eng. 103 129(1989).

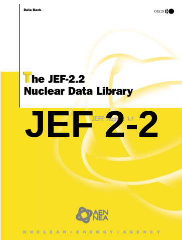


where P_{ni} is the P_n for nuclide i, ($_i$ is the decay constant of i, and $N_i(t)$ is the number of i present at time t after the irradiation. N_i is determined by the initial fuel composition and the irradiation this receives. Therefore to generate the delayed neutron emission rate the irradiation must be specified and a calculation made of the inventory at each time t. However, the total delayed neutron emission per fission, EMBE Paint.Picture , can be calculated by integrating over all time for a single fission. Thus

EMBED Paint.Picture

The total decays of nuclide i per fission, R_i, is equal to the cumulative fission product yield of i; thus, for a pure sample of an actinide, if the cumulative yields, c_i are known the EMBED Paint.Picture can be calculated. Alternatively, if we consider a very long irradiation where all the fission products have reached equilibrium then the activity of each is the cumulative yield, thus producing the same formula. This equivalence is due to the definition of the cumulative yield.

The uncertainty in the calculated EMBED Paint.Picture can be estimated from above, by partial differentiation and assuming c and P_n are independent, as:



Summation calculations of EMBED Paint.Picture

From the equations above values of EMBED Paint.Picture with uncertainties are easily calculated from the JEF2.2 fission product yield and decay data files. This decay data was used to generate the cumulative yields from the independent yields. The values given in Table 1 are quoted per 100 fissions.

The evaluated values are based upon experiment and taken from the following sources; the evaluations of Tuttle (1979)[4], Tuttle (1975) [4A] and Manero (1972) , and where these evaluations do not contain data the experimental values reported by Benedetti and Waldo were used.

As can be seen from Table 1 there is a tendency to over-predict EMBED Paint.Picture for masses below 238 and under-predict those above. The evaluated uncertainties are given as one standard deviation. For the main systems a recent study based upon the currently available experimental data considered the previous evaluated uncertainties to be low, and suggested larger values which should be associated with the results. The uncertainties of the other experimental values measured relative to these are thus also brought into question.

It is interesting to note that the system with the poorest fit to the Z_p model (thermal neutron fission of ^{233}U) also has the worst C/E values.

It must be remembered that these calculations are very sensitive to short lived nuclides far from stability and the P_n values used. Thus study of the sensitivity of these calculations to the Z_p parameters and different P_n data sets will give more information on the properties of the calculations.

Table 1: Calculation of EMBED Paint.Picture **using JEF2.2 decay data and fission yields**

Nuclide	neutron energy	calculated	Measured	Calculated/ Measured
Thorium-232	Fast	6.04559 +/- 4.55E-01	5.47 +/-0.12 T	1.105±0.08

F.Manero and V.A.Konshin: Atomic Eng. Rev. 10, 637(1972).

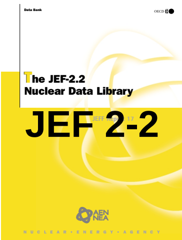
G.Benedetti, A.Cesana, V.Sangiust, M.Terrani and G.Sandrelli: Nucl. Sci. Eng. 80, 379-387(1982).

R.W.Waldo R.A.Karam and R.A.Meyer: Phys. Rev. C. 23, 1113(1981).

“Status of delayed neutron data- 1990”, J.Blachot, M.C.Brady, A.Filip, R.W.Mills and D.R.Weaver. Report of the Nuclear Energy Agency NEACRP-L-323. (1990)

References denoted by letter;

B-Benedetti(1982) M-Manero(1972) T-Tuttle(1975) V-Tuttle(1979) W-Waldo(1981)



Thorium-232
14 MeV
2.93874 +/- 2.52E-01
2.85 +/-0.13 V
1.031±0.10

Uranium-233
Thermal
0.87778 +/- 8.45E-02
0.664+/-0.018 T
1.322±0.10

Uranium-233
Fast
0.95255 +/- 1.15E-01
0.729+/-0.019 T
1.307±0.12

Uranium-233
14 MeV
0.34425 +/- 6.88E-02
0.422+/-0.025 V
0.816±0.21

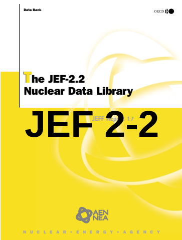
Uranium-234
Fast
1.19717 +/- 1.94E-01
1.06 +/-0.12 T
1.124±0.20

Uranium-235
Thermal
1.70768 +/- 1.17E-01
1.654+/-0.042 T
1.032±0.20

Uranium-235
Fast
1.90981 +/- 2.01E-01
1.714+/-0.022 T
1.166±0.11

Uranium-235
14 MeV
0.78986 +/- 8.16E-02
0.927+/-0.029 V
0.852±0.11

Uranium-236
Fast
2.32978 +/- 2.05E-01
2.31 +/-0.26 T
1.009±0.14



Uranium-238
Fast
4.26631 +/- 2.02E-01
4.510+/-0.061 T
0.946±0.09

Uranium-238
14 MeV
2.39520 +/- 2.06E-01
2.73 +/-0.08 V
0.877±0.16

Neptunium-237
Thermal
1.23220 +/- 1.55E-01
1.07 +/-0.10 W
1.152±0.07

Neptunium-237
Fast
1.23409 +/- 8.88E-02
1.22 +/-0.03 B
1.011±0.16

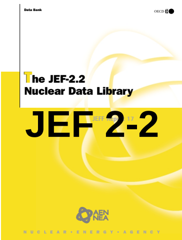
Plutonium-238
Thermal
1.47197 +/- 1.76E-01
0.456+/-0.051 T
3.228±0.20

Plutonium-238
Fast
0.46987 +/- 7.49E-02
0.456+/-0.051 T
1.030±0.19

Plutonium-239
Thermal
0.61740 +/- 5.61E-02
0.624+/-0.024 T
0.989±0.10

Plutonium-239
Fast
0.69008 +/- 7.93E-02
0.664+/-0.013 T
1.039±0.19

Plutonium-240
Fast
0.93974 +/- 1.12E-01
0.96 +/-0.11 T
0.979±0.17



Plutonium-241
Thermal
1.33637 +/- 1.35E-01
1.56 +/-0.16 T
0.857±0.14

Plutonium-241
Fast
1.45238 +/- 9.63E-02
1.63 +/-0.16 T
0.891±0.12

Plutonium-242
Fast
1.92750 +/- 1.39E-01
2.28 +/-0.25 T
0.845±0.13

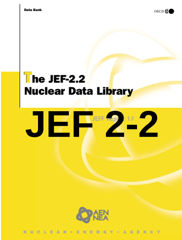
Americium-241
Thermal
0.40910 +/- 6.62E-02
0.44 +/-0.05 W
0.930±0.20

Americium-241
Fast
0.41147 +/- 7.70E-02
0.394+/-0.024 B
1.044±0.20

Americium-242m
Thermal
0.64864 +/- 8.38E-02
0.69 +/-0.05 W
0.940±0.15

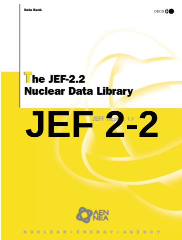
Curium-245
Thermal
0.50695 +/- 8.86E-02
0.59 +/-0.04 W
0.859±0.19

Californium-252
Spontaneous
0.74153 +/- 1.64E-01
0.86 +/-0.10 M
0.862±0.25



Sensitivity of EMBED Paint.Picture **to Z_p Parameters**

The sensitivity of EMBED Paint.Picture to the Z_p parameters was studied by considering the fractional change in EMBED Paint.Picture following a small change in each Z_p parameter used to generate a set of unadjusted yields. These yield sets were not adjusted to fit physical constraints as this would alter the independent yields used in the calculation. This study was made with the UKFY2 fission yields and its corresponding decay data file (Preliminary JEF2 (1991)). Each of the eight parameters **x** was varied in turn by + and **-** 1%, and the sensitivity S(**x**) of to **x** found from:



The results of this calculation are shown in Table 2. This shows the 1% sensitivities to the Z_p parameters for the thermal and fast neutron fission of ^{235}U.

Table 2: Sensitivity of <($_d$> to input Z_p model parameters

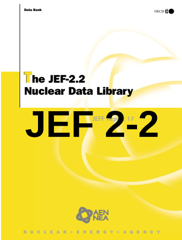
Variations of + and - 10% were also made, but the calculated sensitivities were not found to change significantly. This suggests the sensitivity to the parameters are not rapidly changing.

These results shows that , and are the most important Z_p

EMBED Word.Picture.6

parameters for the calculation of EMBED Paint.Picture . The two parameters and largely determine the shape and positions of the Gaussian fractional independent fission yield distributions, and hence the yields of the neutron-rich precursors. The dependence on reflects the preponderance of odd-Z delayed neutron precursors.

A detailed understanding of how these three Z_p parameters change between different systems would thus improve the results of summation calculations.



Sensitivity of EMBED Paint.Picture **to different P_n sets**

To study the effect of different P_n datasets upon EMBED Paint.Picture , calculations of the equations above were carried out using the UKFY2 cumulative yields with different P_n datasets. It should be noted that if the different P_n values had been used in the production of the UKFY2 they file would alter the predicted cumulative yields. Thus the EMBED Paint.Picture would be altered. However, previous work[9] had showed that for most mass chains these differences in chain yields would be small. This effect was, therefore, ignored for the purpose of this study.

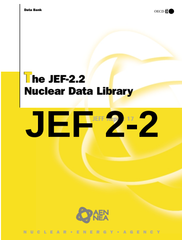
The results for the thermal neutron fission of ^{235}U and ^{239}Pu, and the fast neutron fission of ^{235}U and ^{238}U are shown in Table 3. The number of delayed neutron emitters in each file are shown in the table with a flag to show whether the set includes experimental (E), model prediction (M) or both (EM). Also the results of the two later calculations with the JEF2.2 decay data are shown for comparison.

Table 3: EMBED Paint.Picture **calculated using different P_n datasets.**

Fission yield file	Decay data file	**number of P_n's**	**^{235}U (thermal)**	**^{235}U (fast)**	**^{238}U (fast)**	**^{239}Pu (thermal)**
UKFY2(1990)	JEF2 (1991)	94 EM	1.6354	1.8492	3.9039	0.5884
UKFY2(1990)	Lund(1986)	83 E	1.4455	1.5963	3.5420	0.5050
UKFY2(1990)	Mann(1986)	88 E	1.5665			

Report AEA-TRS-1015 " A new evaluation of fission product yields and the production of a new library (UKFY") of independent and cumulative yield. Part I. Methods and outline of the evaluation" by M.F. James, R.W.Mills and D.R.Weaver (1991).

E is experimental data, M is modelled data and EM is a combination of the two.



1.7629
3.6896
0.5970

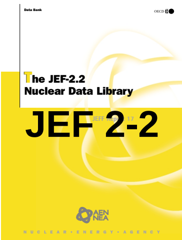
UKFY2(1990)
Brady (1988)
271 EM
1.6995
1.9092
4.0218
0.6131

UKFY2(1990)
Klapdor(1989)
209 M
1.2572
1.4044
3.2950
0.4697

UKFY2(1990)
JEF2 (May 1991)
+ Klapdor (1989)
251 EM
1.6447
1.8541
4.0491
0.5895

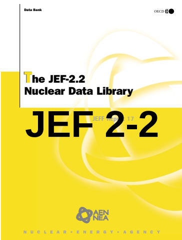
JEF2.2(1993)
JEF2.2 (1993)
165EM
1.7071
1.9092
4.2611
0.6171

This work shows that the majority of the delayed neutron emission comes from precursors whose P_n values have been measured. For the thermal fission of ^{235}U only around 6% of the total for the thermal ^{235}U case comes from modelled P_n values. Interestingly using all modelled P_n values decreases for the value. This may indicated that the modelled P_n values are unrealistically small.



The Keepin six group model

As described above the neutron emission rate following a neutron irradiation can be calculated from an inventory calculation using the equations above. However, in practice, reactor kinetics codes consider a small set of “lumped fission products” with a set of a representative decay constants and yields. This approach was pioneered by Keepin[1] who found that a set of six “lumped fission products” gave a good approximation to measurements.
The six group representation of the delayed neutron activity following a single fission pulse of one ‘average’ fission was thus approximated by Keepin[1] as:



and similarly for a long constant irradiation, producing 1 fission per second, as:

where t is the time after the irradiation, a_k are the normalised group strengths and the ($_k$ are the decay constants for the six delayed neutron emitting groups. For these conditions to be applicable the pulse must be too short for any precursor to decay significantly during the irradiation. Similarly the long irradiation condition only applies if all precursors have reached equilibrium before the end of the irradiation.

It is an interesting result, which also applies to decay heat calculations, that at zero time after the long irradiation the neutron emission is equal to the integral of neutron emission following a single "average" fission pulse over all time after the irradiation.

The fission product yield set used for the following calculations of neutron emission was UKFY2. The decay data used for this work was based upon a preliminary version of JEF2 (1991), with the P_n values extended with the work of Lund and Klapdor . The half-lives were also extended using the Japanese Chart of the Nuclides .

To generate the Keepin six group constants using the UKFY2 data it was first necessary to use the above equations and the inventory code FISPIN to generate the n_{emit} for all 39 fission systems in UKFY2. Both a single fission pulse (10^6 fission/s for 10^{-6}s) and a 'long' irradiation (1 fission/s for 10^{13}s) were modelled. The cooling time steps after the irradiation ranged from zero to 500 seconds. 204 time steps were chosen to reproduce accurately the rapidly changing curves.

The FISPIN code used was a modified version of 6.0 that read in the UKFY2 and JEF2 (1991) decay data in ENDF/B format. The FISPIN calculations used no actinide content or flux but assumed a constant fission rate that produced fission products. The number density and activities of these were then calculated by numerically solving the differential production and decay equations.

The Keepin's six group model was fitted to the pulse and infinite irradiation data simultaneously (i.e. 408 data points) using the Levenberg-Marquardt method as applied by Press et al . The EMBE Paint.Picture values used were taken from the zero time long irradiation results. The results of these calculations are shown in Table 4.

Table 4: Keepin six Group parameters fitted using the UKFY2 fission yields for the 39 fissioning systems.

Nuclide
Group
1
2
3
4
5
6

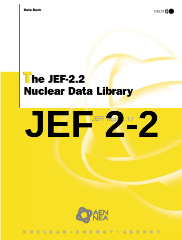
E.Lund, G.Rudstam, K.Aleklett, B.Ekstrom, B.Fogelberg and L.Jabobsson, in Proc. Specialists' meeting on Delayed Neutron Properties, Sept. 1986, Birmingham University, England(1986).

H.V.Klapdor, private communication, March 1989.

Y.Yoshizawa, T.Horiguchi and M.Yamada, The Chart of the Nuclides, INDC(JPN)99/L, Vienna(1984).

J. Soc. Ind. Appl. Math., vol. 11, p431-441. D.W. Marquardt (1967)

"Numerical Recipes: The art of scientific computing", W.H.Press, B.P.Flannery, S.A.Teukolsky and W.T. Vetterling. ISBN 0 521 30811 9. Cambridge University Press (1989).



AM241F
alpha
0.0517
0.3316
0.0876
0.2201
0.2742
0.0349

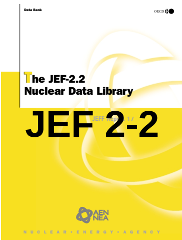
lambda
0.0125
0.0291
0.0633
0.1821
0.4029
2.1434

AM241T
alpha
0.0277
0.1859
0.2184
0.1706
0.3554
0.0420

lambda
0.0124
0.0263
0.0322
0.1346
0.3647
2.0514

AM242MF
alpha
0.0214
0.3612
0.1158
0.3055
0.1556
0.0405

lambda
0.0125
0.0288
0.0882
0.2455
0.5433
2.3395



AM242MT
alpha
0.0235
0.2919
0.0995
0.2062
0.3304
0.0486

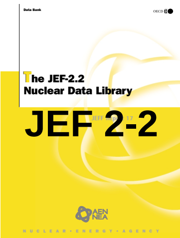
lambda
0.0124
0.0277
0.0385
0.1406
0.3805
2.0568

AM243F
alpha
0.0138
0.3360
0.1433
0.3385
0.1259
0.0424

lambda
0.0125
0.0288
0.0971
0.2813
0.7276
2.5737

AM243T
alpha
0.0136
0.3659
0.1353
0.3261
0.1189
0.0401

lambda
0.0125
0.0287
0.0969
0.2847
0.7465
2.6004



CF252S
alpha
0.0060
0.2134
0.2156
0.2166
0.0521
0.2963

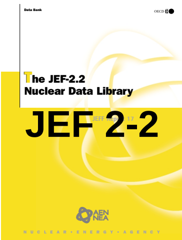
lambda
0.0124
0.0270
0.0306
0.1168
1.5128
0.3892

CM242S
alpha
0.0320
0.1237
0.2618
0.3995
0.0319
0.1511

lambda
0.0124
0.0253
0.0317
0.3523
1.9673
0.1318

CM243F
alpha
0.0362
0.3419
0.1833
0.3126
0.0305
0.0955

lambda
0.0124
0.0279
0.1395
0.3619
1.9644
0.0401



CM243T
alpha
0.0258
0.1980
0.2909
0.1710
0.2871
0.0273

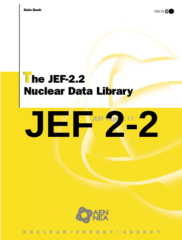
lambda
0.0124
0.0261
0.0314
0.1253
0.3580
1.9313

CM244F
alpha
0.0234
0.3261
0.1266
0.1882
0.2997
0.0360

lambda
0.0124
0.0275
0.0356
0.1322
0.3687
1.9639

CM244S
alpha
0.0177
0.3566
0.1769
0.2772
0.0285
0.1430

lambda
0.0124
0.0275
0.1288
0.3703
2.0649
0.0336



CM244T
alpha
0.0222
0.3035
0.1547
0.1866
0.2958
0.0372

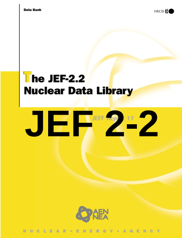
lambda
0.0124
0.0272
0.0341
0.1314
0.3694
1.9630

CM245F
alpha
0.0163
0.2857
0.1616
0.1982
0.2956
0.0427

lambda
0.0124
0.0272
0.0334
0.1282
0.3785
1.9093

CM245T
alpha
0.0173
0.3169
0.0874
0.2168
0.3182
0.0434

lambda
0.0124
0.0278
0.0376
0.1291
0.3786
1.9349



NP237F
alpha
0.0308
0.2198
0.1112
0.3863
0.1804
0.0715

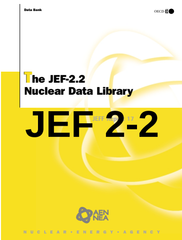
lambda
0.0125
0.0298
0.0863
0.2475
0.5821
2.4425

NP237T
alpha
0.0328
0.2546
0.1169
0.3865
0.1455
0.0638

lambda
0.0125
0.0295
0.0925
0.2653
0.6557
2.5504

NP238F
alpha
0.0201
0.2308
0.1236
0.4023
0.1548
0.0685

lambda
0.0125
0.0294
0.0934
0.2698
0.7263
2.6630



NP238T
alpha
0.0201
0.2638
0.1239
0.3857
0.1374
0.0691

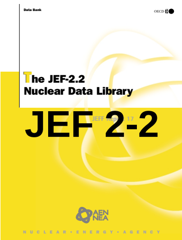
lambda
0.0125
0.0292
0.0962
0.2791
0.8055
2.7287

PU238F
alpha
0.0473
0.2566
0.0816
0.2711
0.2953
0.0481

lambda
0.0125
0.0294
0.0621
0.1832
0.3984
2.1457

PU238T
alpha
0.0294
0.2517
0.0759
0.2886
0.2933
0.0611

lambda
0.0125
0.0291
0.0711
0.1980
0.4156
2.2023



PU239F
alpha
0.0289
0.2719
0.0905
0.3055
0.2476
0.0557

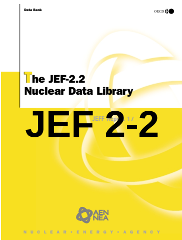
lambda
0.0125
0.0292
0.0737
0.2095
0.4520
2.2679

PU239T
alpha
0.0292
0.2799
0.0982
0.3323
0.2034
0.0569

lambda
0.0125
0.0292
0.0828
0.2322
0.4973
2.3386

PU240F
alpha
0.0193
0.2911
0.1332
0.3735
0.1341
0.0489

lambda
0.0125
0.0289
0.0976
0.2740
0.6601
2.5194



PU241F
alpha
0.0122
0.2516
0.1418
0.3878
0.1475
0.0590

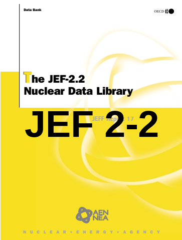
lambda
0.0125
0.0289
0.0998
0.2915
0.8047
2.7593

PU241T
alpha
0.0125
0.2516
0.1344
0.3913
0.1469
0.0634

lambda
0.0125
0.0290
0.0988
0.2888
0.7827
2.7168

PU242F
alpha
0.0081
0.2134
0.1419
0.3957
0.1784
0.0625

lambda
0.0126
0.0289
0.1023
0.3047
0.8744
2.8921



TH232F
alpha
0.0291
0.1177
0.1116
0.4632
0.2070
0.0714

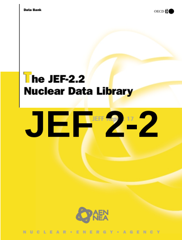
lambda
0.0126
0.0323
0.1058
0.3033
0.9131
2.9891

TH232H
alpha
0.0410
0.1583
0.1148
0.4341
0.1873
0.0645

lambda
0.0125
0.0315
0.0955
0.2706
0.6942
2.4129

U233F
alpha
0.0722
0.0575
0.1894
0.2697
0.3506
0.0605

lambda
0.0124
0.0247
0.0391
0.1542
0.3675
2.0712



U233H
alpha
0.0331
0.1123
0.2809
0.3204
0.0327
0.2206

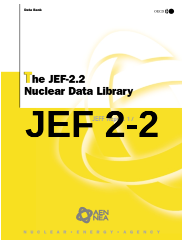
lambda
0.0112
0.0133
0.0357
0.3369
1.8030
0.1338

U233T
alpha
0.0757
0.1915
0.0947
0.3497
0.2256
0.0629

lambda
0.0125
0.0315
0.0685
0.2014
0.4620
2.2332

U234F
alpha
0.0559
0.1957
0.0974
0.3554
0.2316
0.0640

lambda
0.0125
0.0310
0.0726
0.2132
0.4840
2.3218



U235F
alpha
0.0324
0.1605
0.1141
0.4523
0.1533
0.0874

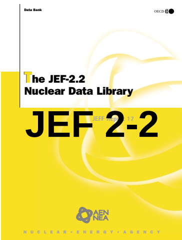
lambda
0.0125
0.0314
0.0922
0.2607
0.7062
2.6802

U235H
alpha
0.0603
0.2223
0.1046
0.2647
0.3028
0.0452

lambda
0.0125
0.0296
0.0528
0.1690
0.3949
2.0373

U235T
alpha
0.0343
0.1974
0.1193
0.4002
0.1745
0.0742

lambda
0.0125
0.0304
0.0903
0.2501
0.6455
2.4599



U236F
alpha
0.0257
0.1681
0.1250
0.4326
0.1703
0.0784

lambda
0.0126
0.0305
0.0977
0.2810
0.8215
2.7776

U238F
alpha
0.0096
0.1198
0.1109
0.4062
0.2469
0.1067

lambda
0.0126
0.0298
0.1038
0.3040
0.9322
3.0302

U238H
alpha
0.0193
0.1768
0.1266
0.4288
0.1832
0.0652

lambda
0.0126
0.0297
0.1010
0.2867
0.8141
2.7951

As well as fitting the twelve a_k and ($_k$ parameters, an attempt was made to fit the six a_k values with a constant set of ($_k$ to allow simplification in reactor calculations where more than one of the nuclides are present.

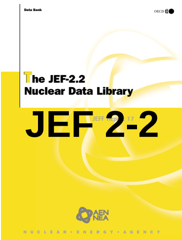
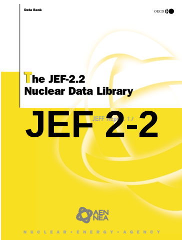


Table 5 contains the fitted a_k values if the set of average ($_k$ values reported by Keepin[1] (Table 4-9, page 91) were used.
Table 6 shows the results of using the set of ($_k$ values from Table 4 for the thermal neutron fission of ^{235}U. The effects of these approximations were then studied. A "maximum percentage deviation" was calculated as the maximum percentage deviation of the fitted curves from the FISPIN calculations. Also a "percentage standard deviation" was calculated as the mean of the percentage deviations of the fitted curves from the FISPIN calculation.
These measures of the goodness of fit are shown in Table 7, Table 8 and Table 9 for the results in Table 4, Table 5 and Table 6 respectively. These tables also include the number of percentage deviations within each of one to five "percentage standard deviations".
As can be seen from these calculations the 12 parameter fits gives the best results. These seldom vary by more than 1% from the calculation. However the two approximations (using the fixed ($_k$ sets) show considerably higher variation from the FISPIN calculations. These differences would not allow accurate reactor calculations and thus the full 12 parameters fits must be used.

Table 5: Fits to the Keepin 6 Group model using the FISPIN code with UKFY2 fission products yields and preliminary JEF2 decay data for the 39 fissioning systems. The lambda's are kept fixed at the 'average' Keepin values. p91 table 4-9.

Group	lambda	AM241F	AM241T	AM242MF
1	0.0127	0.0574	0.0339	0.0247
2	0.0320	0.3873	0.4474	0.4240
3	0.1279	0.1062	0.0172	0.0576
4	0.3040	0.3882	0.4431	0.4196
5	1.3485	0.0545	0.0481	0.0617
6	3.6290	0.0065	0.0102	0.0124



AM242MT
0.0284
0.4229
0.0583
0.4195
0.0599
0.0109

AM243F
0.0161
0.3996
0.0542
0.4291
0.0861
0.0149

AM243T
0.0160
0.4356
0.0295
0.4226
0.0813
0.0151

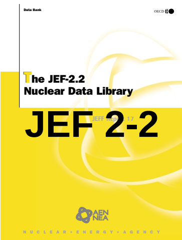
CF252S
0.0082
0.5168
0.0089
0.4009
0.0631
0.0022

CM242S
0.0388
0.4206
0.0204
0.4738
0.0404
0.0059

CM243F
0.0427
0.4653
0.0547
0.3944
0.0369
0.0061

CM243T
0.0320
0.5489
0.0115
0.3736
0.0275
0.0064

CM244F
0.0287
0.5019
0.0315



0.3898
0.0402
0.0079

CM244S
0.0223
0.5675
0.0000
0.3715
0.0316
0.0071

CM244T
0.0274
0.5122
0.0224
0.3891
0.0404
0.0085

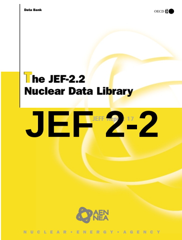
CM245F
0.0206
0.5077
0.0244
0.3899
0.0490
0.0083

CM245T
0.0214
0.4519
0.0622
0.4020
0.0547
0.0077

NP237F
0.0334
0.2472
0.1415
0.4434
0.1122
0.0222

NP237T
0.0361
0.2865
0.1111
0.4395
0.1040
0.0228

NP238F
0.0222
0.2645
0.1140
0.4497
0.1231
0.0265



NP238T
0.0225
0.3036
0.0886
0.4334
0.1211
0.0309

PU238F
0.0518
0.2996
0.1500
0.4217
0.0665
0.0104

PU238T
0.0328
0.2923
0.1141
0.4677
0.0766
0.0166

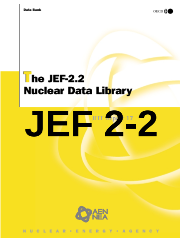
PU239F
0.0321
0.3158
0.1177
0.4416
0.0777
0.0151

PU239T
0.0327
0.3217
0.0991
0.4492
0.0801
0.0172

PU240F
0.0220
0.3397
0.0777
0.4583
0.0854
0.0169

PU241F
0.0140
0.2980
0.0772
0.4612
0.1260
0.0235

PU241T
0.0143
0.2973
0.0730



0.4654
0.1245
0.0254

PU242F
0.0093
0.2558
0.0706
0.4728
0.1680
0.0236

TH232F
0.0299
0.1188
0.1345
0.4688
0.2279
0.0201

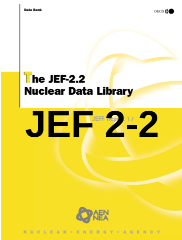
TH232H
0.0427
0.1654
0.1612
0.4623
0.1597
0.0087

U233F
0.0785
0.2056
0.2375
0.3832
0.0849
0.0103

U233H
0.1405
0.2528
0.2523
0.3011
0.0525
0.0008

U233T
0.0791
0.2072
0.2315
0.3732
0.0954
0.0137

U234F
0.0588
0.2140
0.2029
0.4067
0.1026
0.0150



U235F
0.0337
0.1684
0.1846
0.4416
0.1356
0.0360

U235H
0.0648
0.2792
0.2005
0.3758
0.0747
0.0050

U235T
0.0365
0.2156
0.1712
0.4245
0.1310
0.0213

U236F
0.0272
0.1835
0.1463
0.4464
0.1670
0.0295

U238F
0.0104
0.1369
0.0928
0.4469
0.2675
0.0454

U238H
0.0210
0.1995
0.1152
0.4768
0.1665
0.0210

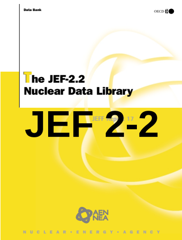
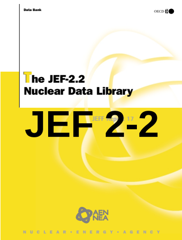


Table 6: Fits to the Keepin six Group model using the FISPIN code with UKFY2 fission products yields and preliminary JEF2 decay data for the 39 fissioning systems. The Lambdas being fixed at the U235T values from this work.

Group	lambda	AM241F	AM241T	AM242MF	AM242MT
1	0.0125	0.0536	0.0311	0.0226	0.0261
2	0.0304	0.3633	0.4248	0.3975	0.3970
3	0.0903	0.0868	0.0121	0.0449	0.0468
4	0.2502	0.3593	0.3969	0.3873	0.3835
5	0.6454	0.1134	0.1068	0.1101	0.1126
6	2.4580	0.0237	0.0283	0.0376	0.0340



AM243F
0.0146
0.3723
0.0453
0.3828
0.1348
0.0502

AM243T
0.0145
0.4071
0.0296
0.3705
0.1292
0.0489

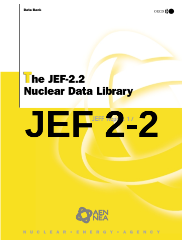
CF252S
0.0073
0.4813
0.0202
0.3502
0.1172
0.0238

CM242S
0.0358
0.3996
0.0144
0.4182
0.1148
0.0172

CM243F
0.0394
0.4400
0.0436
0.3695
0.0889
0.0187

CM243T
0.0293
0.5203
0.0126
0.3497
0.0708
0.0174

CM244F
0.0262
0.4733
0.0282
0.3620
0.0865
0.0237



CM244S
0.0203
0.5384
0.0000
0.3503
0.0704
0.0206

CM244T
0.0250
0.4836
0.0209
0.3604
0.0850
0.0249

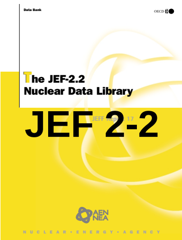
CM245F
0.0187
0.4769
0.0256
0.3565
0.0944
0.0279

CM245T
0.0195
0.4225
0.0512
0.3746
0.1038
0.0283

NP237F
0.0312
0.2284
0.0991
0.4119
0.1615
0.0679

NP237T
0.0336
0.2675
0.0786
0.4021
0.1519
0.0663

NP238F
0.0205
0.2445
0.0811
0.4067
0.1682
0.0790



NP238T
0.0207
0.2824
0.0648
0.3893
0.1566
0.0862

PU238F
0.0486
0.2791
0.1061
0.4108
0.1211
0.0343

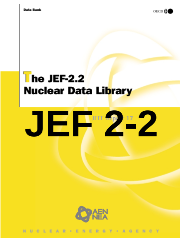
PU238T
0.0304
0.2731
0.0748
0.4429
0.1314
0.0474

PU239F
0.0298
0.2939
0.0842
0.4150
0.1317
0.0454

PU239T
0.0303
0.3010
0.0688
0.4174
0.1328
0.0497

PU240F
0.0202
0.3175
0.0538
0.4186
0.1381
0.0518

PU241F
0.0128
0.2759
0.0579
0.4016
0.1756
0.0762



PU241T
0.0130
0.2755
0.0545
0.4047
0.1740
0.0783

PU242F
0.0084
0.2350
0.0561
0.3873
0.2217
0.0915

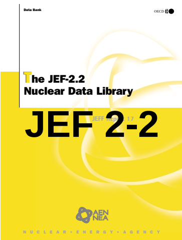
TH232F
0.0284
0.1061
0.0972
0.3697
0.2951
0.1035

TH232H
0.0405
0.1498
0.1155
0.3976
0.2344
0.0623

U233F
0.0751
0.1854
0.1700
0.3954
0.1342
0.0399

U233H
0.1351
0.2286
0.1973
0.3235
0.1011
0.0144

U233T
0.0756
0.1875
0.1655
0.3844
0.1373
0.0497



U234F
0.0559
0.1946
0.1458
0.3962
0.1547
0.0528

U235F
0.0319
0.1525
0.1233
0.4248
0.1718
0.0958

U235H
0.0614
0.2553
0.1546
0.3669
0.1340
0.0278

U235T
0.0343
0.1973
0.1196
0.4002
0.1743
0.0743

U236F
0.0255
0.1673
0.1028
0.3941
0.2121
0.0983

U238F
0.0096
0.1241
0.0671
0.3467
0.2907
0.1618

U238H
0.0195
0.1832
0.0808
0.4054
0.2257
0.0854

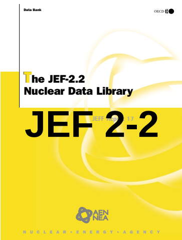
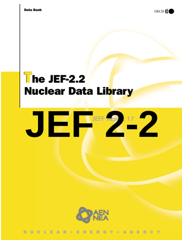


Table 7: Differences between FISPIN calculation and six group model using the 12 parameter fits of Table 4.

System	Maximum % diff	%SD	number of points within standard deviations				
			1	2	3	4	5
AM241F	0.634	0.1327	296	377	406	407	408
AM241T	0.874	0.1952	295	380	406	407	408
AM242MF	0.598	0.1577	266	395	406	407	408
AM242MT	1.05	0.2275	303	382	406	407	408



AM243F
0.522
0.1715
262
394
407
408
408

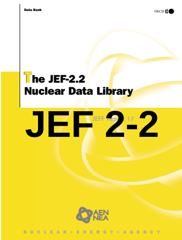
AM243T
0.497
0.1651
259
393
407
408
408

CF252S
0.989
0.2018
322
377
405
406
408

CM242S
0.617
0.1524
281
384
406
407
408

CM243F
0.616
0.1365
302
382
406
407
408

CM243T
0.623
0.1461
285
382
406
407
408



CM244F
0.816
0.1797
304
379
406
407
408

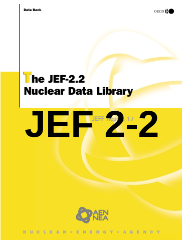
CM244S
0.778
0.1704
306
377
406
407
408

CM244T
0.843
0.1870
300
379
406
407
408

CM245F
1.02
0.2196
302
379
406
407
408

CM245T
1.02
0.2192
304
379
406
407
408

NP237F
0.916
0.2378
272
395
406
407
408



NP237T
0.756
0.2158
273
398
406
407
408

NP238F
0.759
0.2494
265
392
407
408
408

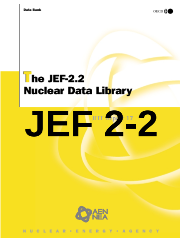
NP238T
0.682
0.2318
264
392
408
408
408

PU238F
0.755
0.1550
300
376
406
407
408

PU238T
0.835
0.1779
291
383
406
407
408

PU239F
0.856
0.1930
286
388
406
407
408

PU239T
0.779
0.1867
281
391



406
407
408

PU240F
0.586
0.1756
261
395
407
408
408

PU241F
0.599
0.2067
260
394
408
408
408

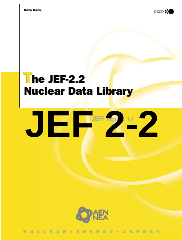
PU241T
0.667
0.2142
261
394
407
408
408

PU242F
0.645
0.2310
262
393
408
408
408

TH232F
0.918
0.3220
268
390
408
408
408

TH232H
0.880
0.2631
271
391
407
408
408

U233F



1.13
0.2397
306
382
406
407
408

U233H
0.602
0.1822
272
390
407
408
408

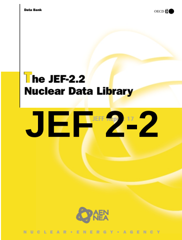
U233T
0.984
0.2023
296
380
406
407
408

U234F
1.01
0.2250
290
386
406
407
408

U235F
0.910
0.3023
271
391
407
408
408

U235H
0.844
0.1641
306
374
405
406
408

U235T
0.907
0.2648
272
394
407



408
408

U236F
0.800
0.2936
270
390
408
408
408

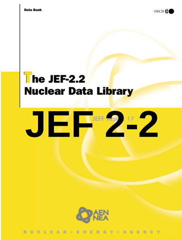
U238F
0.976
0.3470
262
394
408
408
408

U238H
0.730
0.2674
263
389
408
408
408

Table 8: Differences between FISPIN calculation and six group model using the 6 parameter fits of Table 5.

System
Maximum % diff
%SD
number of points within standard deviations

1
2
3
4
5



AM241F
5.277
1.76997
284
384
408
408
408

AM241T
12.41
4.46131
277
379
408
408
408

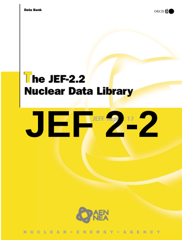
AM242MF
13.37
4.70202
282
377
408
408
408

AM242MT
12.15
4.27126
280
377
408
408
408

AM243F
16.25
5.68500
286
374
408
408
408

AM243T
17.26
6.07802
288
375
408
408
408

CF252S
25.32
8.87814
298
373
408
408
408



CM242S
10.413
3.71415
278
381
408
408
408

CM243F
10.087
3.56741
278
380
408
408
408

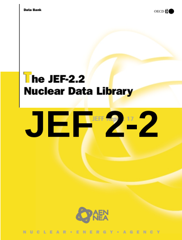
CM243T
14.45
5.19135
282
377
408
408
408

CM244F
14.12
5.02283
282
377
408
408
408

CM244S
18.07
6.45693
286
374
408
408
408

CM244T
14.86
5.30635
283
378
408
408
408

CM245F
16.99
6.01770
289
374
408
408
408



CM245T
15.33
5.38727
288
376
408
408
408

NP237F
4.569
1.50362
282
383
404
405
408

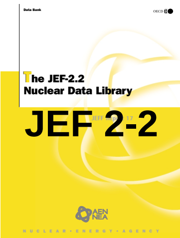
NP237T
6.313
2.14711
281
381
408
408
408

NP238F
8.396
2.82976
285
379
408
408
408

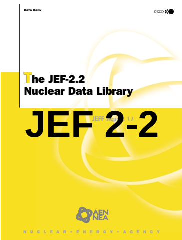
NP238T
10.202
3.51224
280
378
408
408
408

PU238F
3.424
1.10436
290
381
403
404
408

PU238T
7.043
2.38741
282
381
408
408
408



PU239F	7.266	2.43468	283	379	408	408	408
PU239T	8.150	2.80030	280	381	408	408	408
PU240F	12.38	4.33948	280	377	408	408	408
PU241F	14.27	4.93830	287	376	408	408	408
PU241T	13.99	4.84020	286	376	408	408	408
PU242F	15.93	5.50193	289	374	408	408	408
TH232F	-5.790	2.18133	286	388	408	408	408



TH232H
-3.996
1.48478
298
384
408
408
408

U233F
5.535
1.90107
279
384
408
408
408

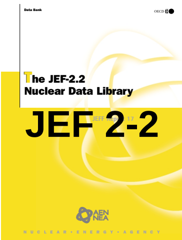
U233H
6.293
2.20002
274
386
408
408
408

U233T
5.270
1.70830
278
387
407
408
408

U234F
4.161
1.30596
276
387
406
407
408

U235F
3.424
1.06953
284
382
406
407
408

U235H
3.385
1.02755
291
378
406
407
408



U235T
2.201
0.873311
279
388
408
408
408

U236F
-2.949
1.15692
281
383
408
408
408

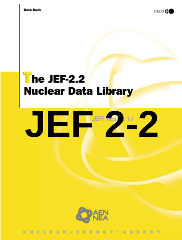
U238F
7.688
2.81241
266
387
408
408
408

U238H
6.469
2.27519
269
385
408
408
408

Table 9: Differences between FISPIN calculation and six group model using the 6 parameter fits of Table 6.

System
Maximum % diff
%SD
number of points within standard deviations

1
2
3
4
5



AM241F
2.214
0.75101
282
387
408
408
408

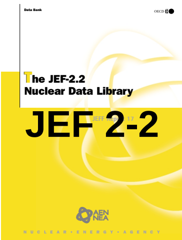
AM241T
6.570
2.3247
283
379
408
408
408

AM242MF
7.023
2.4645
285
378
408
408
408

AM242MT
6.302
2.2019
284
380
408
408
408

AM243F
8.813
3.0941
289
378
408
408
408

AM243T
9.395
3.2845
291
378
408
408
408



CF252S
14.60
5.1432
294
377
408
408
408

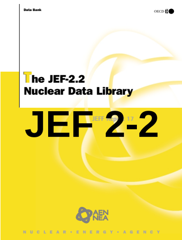
CM242S
5.261
1.8496
283
381
408
408
408

CM243F
5.085
1.7735
282
381
408
408
408

CM243T
7.742
2.7373
284
378
408
408
408

CM244F
7.502
2.6415
286
378
408
408
408

CM244S
9.910
3.4796
289
377
408
408
408



CM244T
7.968
2.8137
284
378
408
408
408

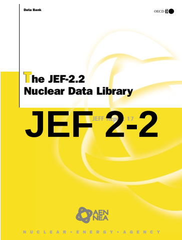
CM245F
9.262
3.2679
287
377
408
408
408

CM245T
8.375
2.9641
288
378
408
408
408

NP237F
1.761
0.58613
290
384
407
408
408

NP237T
2.854
0.99391
278
385
408
408
408

NP238F
3.936
1.3428
285
382
408
408
408



NP238T
5.033
1.7493
284
380
408
408
408

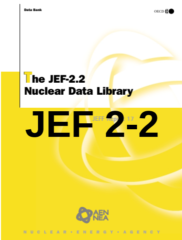
PU238F
-1.145
0.39214
304
383
408
408
408

PU238T
3.190
1.0934
284
384
408
408
408

PU239F
3.253
1.0866
282
381
408
408
408

PU239T
3.888
1.3463
281
383
408
408
408

PU240F
6.560
2.3255
283
380
408
408
408



PU241F
7.637
2.6771
288
378
408
408
408

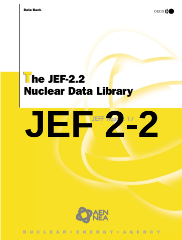
PU241T
7.396
2.5772
288
378
408
408
408

PU242F
8.639
3.0112
291
378
408
408
408

TH232F
-3.171
1.2232
281
390
408
408
408

TH232H
-2.119
0.81461
285
387
408
408
408

U233F
-3.552
1.3251
286
382
408
408
408



U233H
-3.740
1.4532
279
383
408
408
408

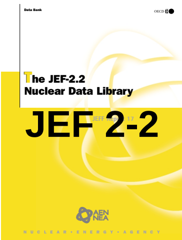
U233T
-3.151
1.1599
289
378
408
408
408

U234F
-2.511
0.94849
284
384
408
408
408

U235F
2.561
0.91626
286
382
408
408
408

U235H
-2.024
0.77499
283
382
408
408
408

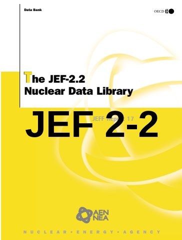
U235T
0.9155
0.26491
273
395
406
407
408



U236F
1.840
0.34728
301
390
403
404
408

U238F
3.547
1.2526
283
384
408
408
408

U238H
2.938
1.0309
282
385
408
408
408



The following figures are an example of the results obtained from the calculations. They show the delayed neutron emission rates for the thermal neutron fission of ^{235}U and ^{239}Pu, and the fast neutron fission of ^{238}U. Both the pulse and long irradiation results are shown. To show this work in context the figures plot the results of the FISPIN calculation, the six group parameter calculations and the six group parameters published by other workers relative to the FISPIN calculation.
The other workers who have published complete six group parameters include Keepin[1], Brady and England[5] and Waldo[9]. The work of Keepin and Waldo are based upon experimental measurements.
The differences from the "long" irradiation case FISPIN results are shown for each of the six group parameter sets in a second figure.
When comparing the results it should be born in mind that experiments have difficulty in measuring the neutron emission at very long times after irradiation due to the fall off of the delayed neutron emission to below the experimental noise. Also, the short lived groups cannot be measured directly as moderated neutrons from the irradiation will still be present. One common technique to measure the short lived groups is to use a pulsed irradiation. The long-lived groups and the moderated neutrons then become a background that can be subtracted. However, at very short times, this background will swamp the neutron emission being measured. Thus the short and long measurements will not be as accurate as those at the middle of the range. Also the accuracy of the six group model will be less than that for EMBE Paint.Picture .
The six group half-lives vary from ~0.2 to 60 seconds. Thus if any neutron emission occurs outside of this time window it cannot be accurately represented by the model.
The majority of the differences in these figures can be attributed to the different values of EMBE Paint.Picture used in the calculations. This can be seen on the figures showing the differences, because at zero time after the "long" irradiation the neutron emission rate will equal the value. Thus the differences at zero time are directly related to the values used.
In the region up to 200 seconds the remaining differences are of the same order as the uncertainty on EMBED Paint.Picture . For times greater than 200 seconds the neutron emission has dropped to such a level that the differences have no practical significance.

Figure 1: The delayed neutron emission rate following a pulse and long irradiation for the thermal neutron fission of ^{235}U.

Figure 2: Percentage difference between the long irradiation FISPIN calculations and 6 group parameters for the thermal neutron fission of ^{235}U

Figure 3:The delayed neutron emission rate following a pulse and long irradiation for the thermal neutron fission of ^{239}Pu.

Figure 4:Percentage difference between the long irradiation FISPIN calculations and 6 group parameters for the thermal neutron fission of ^{239}Pu

Figure 5:The delayed neutron emission rate following a pulse and long irradiation for the fast neutron fission of ^{238}U.

Figure 6: Percentage difference between the long irradiation FISPIN calculations and 6 group parameters for the fast neutron fission of ^{238}U.

Conclusions

Above we have shown reasonable agreement between summation calculations and experimental measurements. This suggests that the JEF2.2 fission product yields and decay data give a good approximation to physical reality. However, it must be stressed that the above delayed neutron calculations were carried out to test the JEF2.2 yield and decay data. The calculated delayed neutron parameters are therefore not recommended for applications as no comprehensive analysis has been made of all the available delayed neutron measurements to validate this work.

Since the completion of these calculations, earlier this decade, there has been much work carried out as part of the WPEC sub-group 6, which will soon be published. This includes a compilation of all the published delayed neutron data parameters. Also included is interesting new work based upon fitting the delayed neutron emission to a larger number of delayed neutron groups, but where a group is dominated by one precursor the time constant is assumed to be the decay of this nuclide. We direct the interested reader to the Sub-group 6 report and reference therein.

Acknowledgements

We would like to thank all those who have examined, discussed and debated this work, especially Drs. Blachot, Brady, England, Filip and Nordborg.

Finally, we would like to thank BNFL for funding this work.