This work was supported by the US Department of Energy, Office of Nuclear Energy, Office of Reactor Research and Technology.

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Application of Adjusted Data in Calculating Fission-Product Decay Energies and Spectra

D. C. George  
R. J. LaBauve  
T. R. England
APPLICATION OF ADJUSTED DATA IN CALCULATING FISSION-PRODUCT DECAY ENERGIES AND SPECTRA

by

D. C. George, R. J. LaBauve, and T. R. England

ABSTRACT

The code ADENA, which approximately calculates fission-product beta and gamma decay energies and spectra in 19 or fewer energy groups from a mixture of $^{235}\text{U}$ and $^{239}\text{Pu}$ fuels, is described. The calculation uses aggregate, adjusted data derived from a combination of several experiments and summation results based on the ENDF/B-V fission-product file. The method used to obtain these adjusted data and the method used by ADENA to calculate fission-product decay energy with an absorption correction are described, and an estimate of the uncertainty of the ADENA results is given.

Comparisons of this approximate method are made to experimental measurements, to the ANSI/ANS 5.1-1979 standard, and to other calculational methods. A listing of the complete computer code (ADENA) is contained in an appendix. Included in the listing are data statements containing the adjusted data in the form of parameters to be used in simple analytic functions. These fitted parameters can be abstracted for other uses such as in spatial neutron depletion or thermal hydraulics codes.

I. INTRODUCTION

Summation calculations of fission product decay energy based on four different fission-product data files were compared with several experiments,1,2,3,4,5 and the results were reported in Ref. 6. The conclusions drawn from these comparisons include

(1) The experimental spectral data are consistent.
(2) Aggregate beta and gamma spectral decay energies calculated from any of the four fission product files do not agree well with experiment for short irradiation and cooling times below \(\sim 1000\) s.

(3) It is likely that some data in ENDF/B-V (Mod 0)\(^7\), probably the experimental decay energies for some individual, high-Q nuclides, are deficient.

These conclusions imply that better estimates of decay spectra will result from calculations that use aggregate data derived, where possible, from experiments rather than data derived entirely from the fission-product files. However, because such experimental data are available only in the region \(2.2 \text{ s} - 2 \times 10^5 \text{ s}\) for gamma decay energy and \(2.2 \text{ s} - 10^4 \text{ s}\) for beta decay energy, information based on ENDF/B-V summation calculations was incorporated to extend the range of the calculated decay-energy cooling times from \(10^4 - 10^9\) s. The method used to prepare the adjusted data base is described in Section II.

The code ADENA uses these adjusted data to calculate fission-product decay-energy spectra from any mixture of thermally irradiated \(^{235}\text{U}\) and \(^{239}\text{Pu}\) fuels at user specified cooling times. A correction for neutron absorption in the fission products is included. Section III contains a description of the code, and Appendix A contains a full listing and a sample problem input and output. The spectra, but not the absorption correction, should be almost as accurate for the fissions induced by fast energy neutrons as it is for thermal neutrons.

Section IV contains the results of three applications of the code ADENA. First, the ADENA results for a finite irradiation problem including the effects of neutron absorption are compared with CINDER-10 (Ref. 8) calculations. Second, sample calculations of both the Oak Ridge and Los Alamos experiments are compared with the experiments. Third, a calculational comparison of the summed spectra with the ANSI/ANS-5.1-1979 standard\(^9\) is made.

Finally, Section V contains the authors' estimate of the reliability of ADENA results. Appendix B clarifies the procedure used to obtain this estimate and includes in tabular form the detailed data upon which the estimate is based.

II. PREPARATION OF ADJUSTED DATA

The adjusted data base used by ADENA is derived from a combination of experimental data and the ENDF/B-V fission-product data file. The experiments, whose results were incorporated into the data base, were conducted at Los Alamos and Oak Ridge; nuclear fuel samples were irradiated with thermal neutrons and
the decay-energy and beta-ray and/or gamma-ray spectra of the resulting fission products measured. Results of these experiments were included in formulating the ANSI/ANS-5.1 Decay Power Standard. A brief summary of the experimental range of data follows.

- Oak Ridge spectral experiments\(^1,2\) in which \(^{235}\text{U}\) and \(^{239}\text{Pu}\) fuels were irradiated with thermal neutrons for times of 1, 10, (5 for \(^{239}\text{Pu}\)), and 100 s, and both aggregate fission-product gamma-ray and beta-ray decay-energy spectra were measured for a range of average cooling times from 2.2 (for the 1-s irradiation time) to 12 000 s (for the 100-s irradiation time). There were similar measurements for \(^{241}\text{Pu}\).

- Los Alamos calorimetric experiments\(^3,4\) in which \(^{233}\text{U},^{235}\text{U},\) and \(^{239}\text{Pu}\) were irradiated with thermal neutrons for 20 000 s and total decay heat (gamma plus beta) measured for a range of cooling times from 29-190 000 s.

- Los Alamos spectral experiments\(^5\) in which fuels, irradiation time, and cooling time ranges were the same as for the calorimetric experiments, but aggregate fission-product gamma-ray decay-energy spectra were measured.

The ENDF/B-V fission-product data file contains data for 877 nuclides, of which 264 have spectra, and there are 20 yield sets. These data for individual nuclides were input to the summation code CINDER-10,\(^8\) and the associated code system described in Refs. 10 and 11 was used to produce calculated decay energies and spectra. The aggregate experimental and summation code results were combined to produce the adjusted data base using the procedure described below.

Step 1: Use ENDF/B-V based summation results to calculate points from \(10^4\) s (beta) or \(2 \times 10^5\) s (gamma) to \(10^9\) s following a fission pulse. (As noted below, calculations for shorter times were included in the detailed procedure.)

Step 2: Use the shape of the ENDF/B-V derived decay-energy curves below 2 s cooling time shifted to coincide with the experimental data having the shortest cooling times to calculate points below 2 s.

Step 3: Combine points from steps one and two with experimental data points. Use this set of combined points as input to FITPULS\(^11\) to calculate a set of parametric pairs, which represents a fit for a combined adjusted equivalent pulse.

A more detailed description of the procedure outlined in these three steps follows.
Methods described in Refs. 10 and 11 were used to create sets of alpha (α), lambda (λ) parameter pairs which represent least squares fits to the aggregate ENDF/B-V pulse data by fitting the data with the equation,

\[ f(t) = \sum_{i=1}^{n} \alpha_i e^{-\lambda_i t} \text{(MeV/fis-s)} \quad (1) \]

These sets of parameter pairs were obtained for beta- and gamma-ray decay, for both ²³⁵U and ²³⁹Pu fuels, for all decay-energy groups, over the full cooling time range of 10⁻⁴-10⁹ s. The generation of these sets was a necessary preliminary step to obtaining the adjusted data base, and the sets are used in each of the three steps previously outlined.

**Long Cooling Times - Step 1**

The sets of parameters from the ENDF/B-V calculation were used in Eq. (1) to compute the beta- and gamma-ray decay energy at four cooling times per decade from the longest experimental cooling time (10⁴ s for beta-ray decay and 2 x 10⁵ s for gamma-ray decay) up to 10⁹ s for each decay energy group for both fuels. Because of large experimental errors, ENDF/B-V data were used to calculate points from 10³-10⁹ s for some of the higher energy groups.

**Cooling Times Less Than Two Seconds - Step 2**

Because there is often a large difference between the decay energy for short cooling times calculated from the ENDF/B-V fits and the experimentally measured values, we used the shape of the ENDF/B-V data shifted to coincide with the equivalent experimental short cooling time points. [The derivation of "equivalent experimental points" (pulse values) is discussed below.] The shift was accomplished by first plotting the ENDF/B-V fit and the equivalent experimental pulse points having a cooling time less than 10 s. Figure 1 is an example of one of these plots. The ENDF/B-V curve was then shifted manually to coincide with the equivalent experimental points, and values for cooling times of 0.01, 0.03, 0.1, 0.3, and 1.0 seconds were read off the graph. (Figure 2 shows the resulting adjusted fit for cooling times less than 10 s after the procedures described in Steps 1-3 have been completed.)

It is important to note that the equivalent experimental points plotted on Figs. 1-3 are produced from the original data in the following manner. The original experimental points are measured beta- or gamma-ray decay energies at cooling times of t seconds after an irradiation period of T seconds. In order
Fig. 1. Beta-ray fission-product decay energy for Group 5 (0.6–0.8 MeV) calculated from ENDF/B-V data and "equivalent pulse" experimental points.

Fig. 2. Beta-ray fission-product decay energy for Group 5 (0.6–0.8 MeV). Adjusted curve shows the result of shifting the ENDF/B-V curve to coincide with the "equivalent pulse" experimental points.
Fig. 3. Gamma-ray decay energy for Group 7 (1.0–1.2 MeV) showing "equivalent pulse" experimental points, ENDF/B-V fit, and adjusted fit.
to intercompare experiments with different irradiation times and to compare these experiments to calculations, it is desirable to reduce the experimental data to equivalent pulse data that are independent of irradiation time. The code FITPULS can generate a set of alphas and lambdas by fitting the original experimental data with an integration of Eq. (1) over $T$ for a unit fission rate producing functions of the form,

$$F(T,t) = \sum_{i=1}^{n} \frac{a_i}{\lambda_i} e^{-\lambda_i t} \left( 1 - e^{-\lambda_i T} \right) \text{(MeV/fis)} .$$  \hspace{1cm} (2)

The set of alpha, lambda parameter pairs derived by FITPULS using Eq. (2) from the combination of all experimental data points constitute the experimental pulse fit. See Appendix D of Ref. 10 for a detailed treatment of this subject. During this fitting process, the percent differences of the original experimental data points to the fitted results as calculated by Eq. (2) are computed and saved. These percent differences can be applied to the experimental pulse by evaluating Eq. (1) at the cooling times of the original experimental points and adding the percent differences to generate equivalent experimental pulse data points. Because the fitting procedure involves a nonlinear least squares algorithm, neither the experimental pulse fits nor the equivalent experimental pulse points are unique. For graphical comparisons, the equivalent experimental pulse values are an excellent representation of the experiments because deviations are emphasized. The actual fitting process of Step 3 (below) uses the original experimental data points, not the equivalent points.

**Final Parameters Representing the Adjusted Data - Step 3**

Points from Step 1 computed directly using the ENDF/BV pulse parameters in Eq. (1) for long cooling times, points from Step 2 derived from the shifted ENDF/BV pulse fit for short cooling times, and the original experimental data points for the middle cooling time region were combined. The combination was input along with the ENDF/BV pulse parameters to FITPULS, which produced sets of alpha, lambda parameter pairs constituting the adjusted equivalent pulse fits. FITPULS uses a nonlinear least squares procedure to fit the input to Eq. (1) (for the pulse points from Steps 1 and 2) and Eq. (2) (for the original experimental finite-irradiation data points) using the ENDF/B-V pulse parameters as the starting values for the fitting process. Thus, the adjusted
fits reflect the basic shape of the ENDF fit, as can be seen in Fig. 3, which shows the original ENDF fit, the final adjusted fit, and the equivalent pulse experimental data points for each experiment. The fitting procedure allows for weights to be assigned to the data points (experimental data or points created by the methods described in Steps 1 and 2). By looking at graphs of the equivalent experimental points and the ENDF fits, it can be determined which points should be given light weights and which should be given heavy weights. Heavy weights will force the final fit to adhere closely to those points, whereas light weights will allow the fit to wander quite far from the data points.

These adjusted fits were obtained in the 19-energy group structure given in Table I for $^{235}$U beta- and gamma-ray decay-energy spectra and for $^{239}$Pu beta- and gamma-ray decay-energy spectra. Note that for cooling times outside the range of the experiments, only ENDF/B-V data were used for FITPULS input; thus the adjusted fits for cooling times greater than $10^4$ s for betas and $2 \times 10^5$ s for gammas are just fits to the calculated ENDF/B-V summation data. Because the experimental error at cooling times greater than 1000 s for energies greater than 4 MeV is very large for groups 17 and 18, those experimental points were ignored and the ENDF/B-V data were used instead. Thus, for these groups the adjusted fits are the ENDF/B-V fits for cooling times greater than 1000 s. There are no experimental data for group 19, therefore the adjusted fit for group 19 is based on the ENDF/B-V fit for all cooling times.

III. DESCRIPTION OF ADENA

The program ADENA was written to approximate the fission product decay-energy spectra with an absorption correction for fuel mixtures of $^{235}$U and $^{239}$Pu. The adjusted fits produced by the procedure given in Sec. II were incorporated into the code, which uses these parameters in Eq. (2) to calculate the fission product decay energy for a finite irradiation time without absorption. A description of the input to ADENA is given in Table II.

For many applications involving long irradiation times, a correction to the adjusted fits is needed to account for the effects of neutron absorption. (Appendix D of Ref. 10 gives the general equations to calculate absorption effects; however, the simplified method developed in Ref. 12 was used in ADENA.) Several limiting assumptions are made in order to simplify the absorption calculations. The power history must be reduced to the associated
TABLE I

ENERGY GROUP STRUCTURE

<table>
<thead>
<tr>
<th>Group</th>
<th>E-Lo(MeV)</th>
<th>E-Hi(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.1</td>
</tr>
<tr>
<td>2*</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>8</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>9</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>1.6</td>
<td>1.8</td>
</tr>
<tr>
<td>11</td>
<td>1.8</td>
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<td>12</td>
<td>2.0</td>
<td>2.2</td>
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<tr>
<td>13</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>14</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>15</td>
<td>2.6</td>
<td>3.0</td>
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<tr>
<td>17</td>
<td>4.0</td>
<td>5.0</td>
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<tr>
<td>18</td>
<td>5.0</td>
<td>6.0</td>
</tr>
<tr>
<td>19</td>
<td>6.0</td>
<td>7.5</td>
</tr>
</tbody>
</table>

*Due to lack of experimental data, Groups 1 and 2 were combined for the beta-ray calculations.

average thermal and epithermal fluxes. The requested group structure must be a subset of the group structure given in Table I. Only the two most important chains $^{155}\text{Eu} - ^{156}\text{Eu}$ and $^{133}\text{Cs} - ^{134}\text{Cs}$ are considered; these have a net positive effect on heating and spectra. The correction is given by the equation

$$
\Delta F(t, T, \phi) = \Delta N(T, \phi) \lambda \omega e^{-\lambda t}
$$

where,

- $T$ is the irradiation time
- $t$ is the cooling time
- $\phi$ is the neutron flux (thermal and epithermal)
- $\lambda$ is the decay constant of the second nuclide in the chain
- $\omega$ is the average photon decay energy for a given group for the second nuclide
- $\Delta N(T, \phi)$ is the change in atom density of the nuclide resulting from its radiative capture and capture in its precursor.
TABLE II
ADENA INPUT SPECIFICATIONS

<table>
<thead>
<tr>
<th>Card</th>
<th>Variable</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UFRAC</td>
<td>Fraction of $^{235}$U in fuel</td>
</tr>
<tr>
<td></td>
<td>TFLUX</td>
<td>Average thermal flux (n/cm²/s)</td>
</tr>
<tr>
<td></td>
<td>ETFLUX</td>
<td>Average epithermal flux (n/cm²/s)</td>
</tr>
<tr>
<td></td>
<td>OTIME</td>
<td>Operating time (seconds) (use OTIME = 0 for pulse case)</td>
</tr>
<tr>
<td></td>
<td>NGI</td>
<td>Number of energy groups</td>
</tr>
<tr>
<td></td>
<td>NTSP</td>
<td>Number of cooling times</td>
</tr>
<tr>
<td></td>
<td>IPLT</td>
<td>Plotting flag; flag = 1 for plots, = 0 for no plots</td>
</tr>
<tr>
<td></td>
<td>IST</td>
<td>If = 1, calculate ANSI Standard, 0 otherwise</td>
</tr>
<tr>
<td>2</td>
<td>EI(I),I=1,NGI+1</td>
<td>If NGI &gt; 0 energy bounds (MeV); energy bounds must be a subset of bounds given in Table I.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If NGI &lt; 0, card 2 is omitted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If NGI = 0, energy bounds of Table I are used</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If NGI = -6, the energy bounds 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 7.5 will be used</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If NGI = -12, the energy bounds 0.0, 0.4, 0.8, 1.0, 1.4, 1.8, 2.2, 2.6, 3.0, 4.0, 5.0, 6.0, 7.5 will be used</td>
</tr>
<tr>
<td>3</td>
<td>TMIN,TMAX</td>
<td>Only if NTSP = 0 or NTSP = -1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If NTSP = 0, results will be calculated for cooling times at each decade and half decade from TMIN to TMAX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>If NTSP = -1, results will be calculated for cooling times at each decade from TMIN to TMAX</td>
</tr>
<tr>
<td></td>
<td>T(I),I=1,NTSP</td>
<td>Only if NTSP &gt; 0, cooling times</td>
</tr>
<tr>
<td>4</td>
<td>UFG,UFB,PUFG,PUFB</td>
<td>Multiplication factor for increasing confidence limits of ADENA calculation for $^{235}$U gamma energies, $^{235}$U beta energies, $^{239}$Pu gamma energies, and $^{239}$Pu beta energies, in that order. Set = 1 for no effect</td>
</tr>
</tbody>
</table>

\*All input is free field; values or commas must be supplied for all variables.
Results are generated for each requested cooling time by group and for the sum over all groups. Beta-ray, gamma-ray, and the sum of beta- and gamma-ray decay energies are printed and plotted for each category.

The ADENA code also has the capability of calculating the decay energy after a pulse (specify OTIME = 0) and of performing calculations of the total beta plus gamma decay energy based on the ANSI/ANS-5.1-1979 Standard (specify IST =1), as described in Table II.

IV. COMPARISONS

To check the data fits used in ADENA, three types of comparisons were made. The first comparison involved using ADENA to calculate the gamma-ray decay energy at three cooling times (1, 10^6, and 10^8 s) for a 235U-fueled thermal reactor with an average thermal flux of 10^{14} n/cm^2/s for an operating time of 20 000 hours. The ADENA results were then compared with the results of a CINDER-10 (Ref. 8) calculation of the same problem. The ADENA calculation used the adjusted data base derived from experiment and ENDF/B-V, whereas the CINDER calculation used ENDF/B-IV data. The results of both calculations are given in Table III. The biggest differences occur at the shortest cooling time, 1 s, in the lowest energy group. This observation is supported by the results of the data testing study^6 that indicates that the calculated gamma-ray decay energies are relatively high for early cooling times and small gamma-ray energies. Maximum absorption effects in the calculations are at 10^6 s cooling time for the europium chain and 10^8 s for the cesium chain. As can be seen from the tabulations in Table III, ADENA agrees well with CINDER at these times.

The second type of comparison involved using ADENA to calculate the Oak Ridge (ORNL) and Los Alamos experiments, and plotting the calculation with the experimental data. Examples of these graphical comparisons for the ORNL 100-s irradiation experiment^1 are given in Figs. 4-6 for three cooling times (90, 950, and 11 950 s) and for the Los Alamos 5.56-h experiment^3 in Figs. 7-9 for three cooling times (128, 1218, and 14 650 s). As can be seen in the figures, the calculation agrees quite well with the experiment. Note that for long cooling times and high gamma-ray energies, the experimental error is very large.

A final comparison is made with the 1979 ANSI/ANS-5.1 Standard. This standard is believed to provide the best estimate of total (beta plus gamma)
TABLE III
COMPARISON OF GAMMA-RAY ENERGY CALCULATED BY ADENA AND CINDER

<table>
<thead>
<tr>
<th>Energy Bounds (MeV)</th>
<th>Cooling Time 1 s Gamma Decay Energy (MeV/fis)</th>
<th>Cooling Time 10^6 s Gamma Decay Energy (MeV/fis)</th>
<th>Cooling Time 10^8 sGamma Decay Energy (MeV/fis)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CINDER</td>
<td>ADENA</td>
<td>CINDER</td>
</tr>
<tr>
<td>1</td>
<td>0.0-1.0</td>
<td>2.681</td>
<td>0.180</td>
</tr>
<tr>
<td>2</td>
<td>1.0-2.0</td>
<td>2.061</td>
<td>1.971</td>
</tr>
<tr>
<td>3</td>
<td>2.0-3.0</td>
<td>0.838</td>
<td>0.968</td>
</tr>
<tr>
<td>4</td>
<td>3.0-4.0</td>
<td>0.306</td>
<td>0.421</td>
</tr>
<tr>
<td>5</td>
<td>4.0-5.0</td>
<td>0.166</td>
<td>0.179</td>
</tr>
<tr>
<td>6</td>
<td>5.0-6.0</td>
<td>0.042</td>
<td>0.057</td>
</tr>
<tr>
<td>Total</td>
<td>6.095</td>
<td>5.856</td>
<td>0.261</td>
</tr>
</tbody>
</table>

Fuel: 235U  
Thermal Flux: 10^{14} n/cm²/s  
Epithermal Flux: 5 x 10^{14} n/cm² s  
Operating Time: 20 000 hr

decay heating, but it does not provide a resolution into the beta and gamma components or spectra. The primary intent of this report is to provide a simple code that will calculate our best estimate of these components, particularly their spectra on a few-energy group basis. The total heating closely matches values from the standard, as shown in Fig. 10 for 235U and Fig. 11 for 239Pu, but is not normalized to the standard. The ADENA results are within 10% of the standard at all times. In terms of the small assigned uncertainties of the standard, the ADENA results are all within a two-sigma uncertainty of the standard for 239Pu. The uncertainties in the standard are much smaller for 235U (<2%), and 14 of the 46 points are further than 2 sigma from the standard (all are within 10%), 4 points are further than 3 sigma, and all are within 4 sigma uncertainty of the standard. Note that the standard is based on five experiments and ENDF/B-IV data, whereas our adjusted fits are based on only three experiments and ENDF/B-V data.

V. ESTIMATE OF ACCURACY OF CALCULATIONS USING THE ADENA CODE

As described in Sec. III, the user has the option of assigning values to four input parameters in ADENA, namely, UFG, UFB, PUFG, and PUFB, which will raise or lower the results of the calculation by a certain percentage and thus increase the level of confidence in the calculation. It is the intent of this
Fig. 4. Gamma-ray decay energy after a cooling time of 90 s from the Oak Ridge National Laboratory 235U 100-s irradiation experiment compared with the ADENA calculation.

Fig. 5. Gamma-ray decay energy after a cooling time of 950 s from the Oak Ridge National Laboratory 235U 100-s irradiation experiment compared with the ADENA calculation.
Fig. 6. Gamma-ray decay energy after a cooling time of 11,950 s from the Oak Ridge National Laboratory 235U 100-s irradiation experiment compared with the ADENA calculation.

Fig. 7. Gamma-ray decay energy after a cooling time of 128 s from the Los Alamos 235U 5.56-h irradiation experiment compared to the ADENA calculation.
Fig. 8. Gamma-ray decay energy after a cooling time of 1218 s from the Los Alamos 235U 5.56-h irradiation experiment compared to the ADENA calculation.

Fig. 9. Gamma-ray decay energy after a cooling time of 14 650 s from the Los Alamos 235U 5.56-h irradiation experiment compared to the ADENA calculation.
Fig. 10. Comparison of ANSI/ANS-5.1-1979 standard for thermal pulse fission of $^{235}\text{U}$ to the ADENA calculation.

Fig. 11. Comparison of ANSI/ANS-5.1-1979 standard for thermal pulse fission of $^{239}\text{Pu}$ to the ADENA calculation.
section to provide the user with some guidance in assigning values to these parameters. Overall reliability of calculations with ADENA depends upon (a) the accuracy of the adjusted spectral fits and (b) the accuracy of the neutron absorption approximation. Some indication of the accuracy of the fits is obtained by the calculation of the standard noted in Sec. IV. Note, however, that this is for the decay energy from combined beta- and gamma-ray decay for the aggregate of the fission products and summed over all energy groups.

Results given in Sec. IV show that the values calculated by ADENA are all within the 2-sigma error quoted for the $^{239}$Pu standard, but that 14 were outside the small 2-sigma error quoted for $^{235}$U. These 14 values are shown as a function of cooling time in Table IV. Note that 9 of the 14 values occur for cooling times of 100 s or less. We therefore suggest that for problems involving totals over energy (i.e., nonspectral) and total beta- plus gamma-decay energy, an average uncertainty value of 7.5% be assumed for cooling times of 100 s or less, and an average of 4.0% be assumed for longer cooling times.

Uncertainties assigned for spectral calculations using the adjusted fits are considerably greater, however, and are more dependent on cooling-time ranges as well as being dependent upon spectral energy ranges. A rather detailed discussion of the deviations of calculations with the adjusted fits from aggregate values from summation calculations using ENDF/B-V and the deviations of adjusted fit calculations from experimental data are given in Appendix B. On the basis of the results of the analysis in this appendix, we recommend that the uncertainties given in Table V be used over the energy and cooling-time ranges given in the table for both beta- and gamma-ray decay energies and for both $^{235}$U and $^{239}$Pu fuels. We further suggest that the user can easily modify this table according to his needs by referring to Appendix B.

Finally, Table III is a good example of the accuracy of the two-chain approximation that the ADENA code uses to calculate neutron absorption effects for cooling times above $10^5$ s. As can be seen from the table, deviations from the summation calculations do not exceed 2% for those cooling-time ranges where the absorption correction is significant. For shorter cooling times, uncertainties in spectral values calculated with the adjusted fits are considerably greater than the deviation due to absorption effects. Consequently, as a "rule of thumb," we suggest that a minimum uncertainty of 10% be assigned in Table V for ADENA calculations with significant absorption effect, i.e., large fluence and long cooling times. Neutron absorption is discussed more fully in Refs. 10 and 12.
TABLE IV
ADENA CALCULATIONS OUTSIDE 2-SIGMA OF $^{235}$U STANDARD

<table>
<thead>
<tr>
<th>Cooling Time (s)</th>
<th>1-Sigma Uncertainty in Standard (%)</th>
<th>Deviation of ADENA Calculation from Standard (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.0E+00</td>
<td>4.3</td>
<td>10.0</td>
</tr>
<tr>
<td>6.0E+00</td>
<td>3.5</td>
<td>8.9</td>
</tr>
<tr>
<td>8.0E+00</td>
<td>3.1</td>
<td>7.6</td>
</tr>
<tr>
<td>1.0E+01</td>
<td>3.2</td>
<td>6.7</td>
</tr>
<tr>
<td>2.0E+01</td>
<td>2.4</td>
<td>6.3</td>
</tr>
<tr>
<td>4.0E+01</td>
<td>2.0</td>
<td>8.1</td>
</tr>
<tr>
<td>6.0E+01</td>
<td>1.9</td>
<td>7.5</td>
</tr>
<tr>
<td>8.0E+01</td>
<td>1.9</td>
<td>6.5</td>
</tr>
<tr>
<td>1.0E+02</td>
<td>1.8</td>
<td>5.7</td>
</tr>
<tr>
<td>2.0E+02</td>
<td>1.9</td>
<td>4.8</td>
</tr>
<tr>
<td>4.0E+02</td>
<td>1.9</td>
<td>4.5</td>
</tr>
<tr>
<td>2.0E+03</td>
<td>1.8</td>
<td>3.9</td>
</tr>
<tr>
<td>2.0E+04</td>
<td>1.4</td>
<td>4.2</td>
</tr>
<tr>
<td>4.0E+04</td>
<td>1.4</td>
<td>3.3</td>
</tr>
</tbody>
</table>

TABLE V
PERCENT ACCURACY OF ADJUSTED SPECTRAL FITS

<table>
<thead>
<tr>
<th>Energy Ranges (MeV)</th>
<th>Cooling-Time Ranges (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.0E-02-1.0E+00</td>
</tr>
<tr>
<td>0.0-0.6</td>
<td>22.8</td>
</tr>
<tr>
<td>0.6-1.6</td>
<td>6.9</td>
</tr>
<tr>
<td>1.6-3.0</td>
<td>27.2</td>
</tr>
<tr>
<td>3.0-7.5</td>
<td>40.5</td>
</tr>
</tbody>
</table>

VI. SUMMARY

A method for creating an adjusted fission-product decay-energy data base from a combination of experimental data and the ENDF/B-V fission-product data file has been described. The code ADENA, which uses the adjusted data base in calculating fission-product decay-energy spectra (including the major effects of neutron absorption) for fuel mixtures of $^{235}$U and $^{239}$Pu, has also been described. The code can be used for a wide variety of reactor operational and safety related computations where aggregate fission-product decay spectra are needed. This avoids the need for the large data base and code systems¹⁰⁻¹² we have used to produce this end product, assuming the user requires only aggregate,
rather than individual nuclide, results. We have, in addition, incorporated the important experimental spectra available for short cooling times.

Several examples of the application of the ADENA code are also given, including a comparison to the ANSI/ANS 5.1-1979 Standard. A section is included from which the user can obtain an indication of the reliability of ADENA calculational results.

The adjusted parameters can be abstracted from the code listing and used directly in Eqs. (1) or (2) or the more general equations in the appendix of Ref. 10 by those users requiring spectral calculations in various spatial codes.

ACKNOWLEDGMENTS

For two fuels, the pulse functions described in this report and the associated ADENA code are the culmination of a series of related reports and codes. The need for and general utility of such functions was originally suggested by J. Lewellen and P. Hemmig (Department of Energy). Along the way, we have enjoyed discussions contributing to our work with R. Schenter, F. Schmittroth, and F. Mann (Hanford Engineering Development Lab); A. Tobias and colleagues (Central Electricity Board, U.K.); and T. Yoshida and colleagues (Nippon Atomic Industry Group Nuclear Research Laboratory, Japan). The experimental data provided by J. K. Dickens (Oak Ridge), and J. Yarnell and E. Jurney (Los Alamos) contributed vitally to this work and to earlier comparisons.

REFERENCES


7. Fission-Product Decay Library of the Evaluated Nuclear Data File, Version V (ENDF/B-V). [Available from and maintained by the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory]. NOTE: Spectral files in these compilations are based on data evaluated at INEL.


APPENDIX A

A full listing of the computer code ADENA is contained in this appendix. The adjusted fits can be abstracted from the block data routine and used in other applications. The fits are in the order $^{235}\text{U}$ betas, $^{235}\text{U}$ gammas, $^{239}\text{Pu}$ betas, and $^{239}\text{Pu}$ gammas. For the beta fit, groups 1 and 2 have been combined; thus, in order to retrieve the fits for group 8 betas, one must abstract the seventh set of parameters. For nonspectral calculations of the total (beta plus gamma) decay energy, the fits to the standard have been included; see subroutine STNDRD.

Input and output listings of a sample problem have been included following the listing of the code. This problem calculates the decay-energy spectra in 12 groups (see Table II), at 2 cooling times ($10^6$ and $10^8$ s), from a reactor whose operating time was $7.2 \times 10^7$ s, with a thermal flux of $10^{14}$ n/cm$^2$/s, an epithermal flux of $5 \times 10^{14}$ n/cm$^2$/s, and with a fuel mixture 75% $^{235}\text{U}$ and 25% $^{239}\text{Pu}$. 
PROGRAM ADENA(INPUT,TAPE5=INPUT,TAPE6.OUTPUT,TAPE1)
ADEN 10
C PROGRAM TO APPROXIMATE FISSION PRODUCT DECAY ENERGY WITH
C ABSORPTION FOR MIXTURES OF PU-239 AND U-235.
ADEN 20
C RESULTS IN 19 GROUP GAMMA 18 GROUP BETA STRUCTURE
ADEN 30
C ABSORPTION CORRECTION FROM CS, EU CHAINS.
ADEN 40
REAL ABCOR(2),AC(50,19,2),W(19,3,2),BET(19),GAM(19),TDT(19)
ADEN 50
REAL AAC(3800)
ADEN 60
EQUIVALENCE (AC(I, I, I, I),AAC(I))
ADEN 70
COMMON /VARI/NGI,EI(20),NTSP,T(50) ,UFRAC,TFLUX,ETFLUX,OTIME .uFG,
ADEN 80
2 UFB,PUFG,PUFB,PIPL,IST
ADEN 90
COMMON /A6Sp/OC,YU,YpU,PEPXS,FEPXS .PTXS,FTXS
ADEN 110
COMMON /FITs/xLAM(20,19,4),xALp(20,19,4),KTRM(19,4)
ADEN 120
FITs IN ORDER U-BETA U-GAMMA PU-BETA PU-GAMMA SEE BLOCK DATA
ADEN 130
C W IS THE AVERAGE DECAY ENERGY FOR SECOND
C NUCLIDE BY GROUPS.
ADEN 140
DATA (W(I,1,1),I=1,19)/.0180922,.0281686,.0768595,.0417469.
ADEN 150
1 .000791733,.0000108118,.618985E-7,1.84582E-6,2.28177E-8.
ADEN 160
2 10+0./
ADEN 170
DATA (W(I,1,2),I=1,19)/.001418678,0...000980157,.141983,1.26973.
ADEN 180
1 .0705032,.0314065,.0415000,.11+0.6/0.
ADEN 190
DATA (W(I,2,1),I=1,19)/.0390261,.0296386,.040872,.0327957.
ADEN 200
1 .0398798,.0423082,.0407609,.0376028,.0315247.
ADEN 210
2 .022194,.016393,.0029791,.0000319913,5+0.6/0.
ADEN 220
DATA (W(I,2,2),I=1,19)/.0141238,.0160603,.00450957.
ADEN 230
1 .0169239,.0964488,.142209,.276996,.255532,.0805968.
ADEN 240
2 .161764,.303278,.0524688,.276996,.255532,.0805968.
ADEN 250
DATA (W(I,3,1),I=1,18)/.0191422,.0426199,.0647785,.017627.
ADEN 260
1 .00236877,.00463174,.35695E-7,1.82712,.171198,.204923,11+0.6/0.
ADEN 270
DATA (W(I,3,2),I=1,18)/.00749719,.00259804,.0487936,.751278.
ADEN 280
1 .82712,.171198,.204923,11+0.6/0.
ADEN 290
CALL FILEREP
ADEN 300
IF(IPLT.EQ.1) CALL GPLDT(IHU,5HPLDTA,5)
ADEN 310
READ INPUT - FREE FIELD
ADEN 320
C CARD 1-FRACTION OF U-235 IN FUEL(UFRAC), AVERAGE THERMAL FLUX
C (TFLUX), AVERAGE EPITHERMAL FLUX(ETFLUX), OPERATING TIME
C (TIME). NUMBER OF ENERGY GROUPS(NGI), NUMBER OF CODDLING
C TIMES(NTSP), PLOTTING FLAG=1 FOR PLOTS; OTHERISE(IPLT).
C STANDARD FLAG =1 TO CALCULATE STANDARD (IST); OTHERISE
C USE OTIME=I FOR BURST CASE
ADEN 330
C CARD 2-IF NGI>0 EI(I), I=1,NGI+1, ENERGY BOUNDS
C -IF NGI>0 USE STANDARD 19 GAMMA 18 BETA GROUPS
C -IF NGI=6 STANDARD 6 GROUP 0..1..2..3..4..5..7..5
C -IF NGI=-12 BUILT IN 12GRP 0..4..8..11..14..18..22..26..30..34..5..7..5
C CARD 3-IF NTSP>0 THEN TMIN, TMAX, RESULTS WILL BE AT EACH DECADE
C AND HALF DECADE FROM TMIN TD TMAX
C - IF NTSP=1 THEN TMIN, TMAX, RESULTS WILL BE AT EACH DECADE
C FROM TMIN TD TMAX
C - IF NTSP>0 THEN T(1)....T(NTSP) MAXIMUM OF 50 TIMES
C CARD 4-ADJUST FACTORS PERCENT TO BE ADDED TO U,PU DECAY ENERGY
C (BETA,GAMMA FOR EACH) UFB,PUFB,PUFB
ADEN 340
C CALL READUS
ADEN 350
C ACCUMULATE ABSORPTION CORRECTION
C CONSIDER ONLY CS 133-134 AND EU 155-156 CHAINS
C USE AC(I,J,K,L) I*CDOLLING TIME, J=GROUP, K=BETA OR GAMMA
C NG=19
C NBG=2
C NFUEL=2
C NCHN=2
C DD 30 I=1,3800
C 30 AAC(I)=0.
C USE PULSE EONS IF DTIME=0.
C IF(DTIME.EQ.0.) GO TO 101
C ABSORPTION CORRECTIONS RETURNED IN ABCOR(1) FDR URANIUM ABCOR(2) FDR
C PLUTONIUM
ADEN 360
DD 100 N=1,NCHN
CALL EVAL(N,ABCDOR)
C LDOR OVER TIME STEPS (I) AND GROUPS (J) TO GET CORRECTIONS
C K INDEX TO NUMBER OF FUELS
C L INDEX TO BETA OR GAMMA CORRECTION
DO 90 L=1,NFUEL
DO 90 K=1,NFUEL
C- 90 d=1,NG
90 AC(I,d,R,L)=AC(I,d,R,L)+ABCDOR(K)*DC*EXP(-DC*T(I))*W(d,N,L)
100 CONTINUE
C CHECK FOR STANDARD CALCULATION
101 IF(IST.EQ.0) CALL STDORD(AC)
C FINAL ACCUMULATION IS BY COOLING TIME
C FOR EACH TIME CALCULATED BETA, GAMMA AND TOTAL DECAY ENERGY FOR
C EACH GROUP
C TAKE APPROPRIATE FRACTION FOR EACH FUEL AND SUM
DD 200 I=1,NTSP
BTOT=GTOT=STOT=O.
DO 150 J=1,NG
BET(J)=O.
GAM(J)=O.
TOD(J)=O.
150 CONTINUE
C BETAS INDICES ARE 1 FOR URANIUM AND 3 FOR PLUTONIUM
IF(J.EQ.19) GO TO 190
KU=KTRM(J,1)
KPU=KTRM(J,3)
U-BETAS
DO 110 K=1,KU
XA=XALP(K,J,1)
XL=XLAM(K,J,1)
IF(DTIME.NE.0.) BET(J)=BET(J)+XA/XL*EXP(-XL*T(I))*(1-EXP(-XL*OTIME))
IF(DTIME.EQ.0.) BET(J)=BET(J)+XA*EXP(-XL*T(I))
110 CONTINUE
TEMP=BET(J)+AC(I,J,1,1)
IF(UFB.LT.1.0E-10) UFB=1.
BET(J)=BET(J)+UFB
PU-BETAS
TEMP=O.
DO 120 K=1,KPU
XA=XALP(K,J,3)
XL=XLAM(K,J,3)
IF(DTIME.NE.0.) TEMP=TEMP+XA/XL*EXP(-XL*T(I))*(1-EXP(-XL*DTIME))
IF(DTIME.EQ.0.) TEMP=TEMP+XA*EXP(-XL*T(I))
120 CONTINUE
TEMP=TEMP+AC(I,J,2,1)
IF(PUBF.LT.1.0E-10) PUBF=1.
TEMP=TEMP+PUBF
C GET FRACTIONS
BET(J)=UFRAC*BET(J)+(1-UFRAC)*TEMP
IF(BET(J).LT.1.0E-10) BET(J)=O.O
C GAMMAS INDICES ARE 2,4
190 KU=KTRM(J,2)
KPU=KTRM(J,4)
C U-GAMMAS
DO 130 K=1,KU
XA=XALP(K,J,2)
XL=XLAM(K,J,2)
IF(DTIME.NE.0.) GAM(J)=GAM(J)+XA/XL*EXP(-XL*T(I))*(1-EXP(-XL*OTIME))
IF(DTIME.EQ.0.) GAM(J)=GAM(J)+XA*EXP(-XL*T(I))
130 CONTINUE
GAM(J)=GAM(J)+AC(I,J,1,2)
IF(UFG.LE.O.) UFG=I.
GAM(J)=GAM(J)*UFG
C PU-GAMMAS
TEMP=0.
DD 140 K=1,KPU
XA=XALP(K,J,4)
XL=XLAM(K,J,4)
IF(DTIME.NE.O.) TEMP=TEMP+XA/XL*EXP(-XL*T(I))*(1-EXP(-XL*DTIME))
IF(DTIME.EQ.O.) TEMP=TEMP+XA*EXP(-XL*T(I))
140 CONTINUE
TEMP=TEMP+AC(1,J,2,2)
IF(PUFG.LE.O.) PUFG=I.
TEMP=TEMP+PUFG
GAM(J)=UFRAC*GAM(J)+(1-UFRAC)*TEMP
IF(GAM(J).LT.1.E-10) GAM(J)=O.O
C ACCUMULATE TOTALS
TDT(J)=GAM(J)
IF(J.NE.1) TDT(J)=TDT(J)+BET(J-1)
BTD=TBDT+BET(J)
GTD=TGTDT+GAM(J)
STOT=STOT+TDT(J)
C CONTINUE
C REGROUP IF NECESSARY
CALL REGGROUP(BET,GAM,TOT)
C OUTPUT SECTION
WRITE (6,151)
151 FDSMAT(1H1,T20,"FISSION PRODUCT DECAY ENERGY FOR A MIXTURE OF U-23")
15 AND PU-239")
TEMP=(1.-UFRAC)*100.
TEMP+UFRAC*100.
WRITE (6,152) TEMP,TFLUX,ETFLUX,DTIME,T(I)
152 FDSMAT(150,"PERCENT U-235",T50,1PE11.4/
1 T30,"PERCENT PU-239",T50,1PE11.4/
2 T30,"THERMAL FLUX",T50,1PE11.4," N/CM**2-S*/
3 T30,"EPITHERMAL FLUX",T50,1PE11.4," N/CM**2-S*/
4 T30,"OPERATING TIME",T50,1PE11.4," SECONDS")/
5 T30,"COOLING TIME",T50,1PE11.4," SECONDS")
WRITE (6,160)
160 FDSMAT(1H0,T10,
2 GRP LDO " EHI BETA DECAY ENERGY GAMMA DECAY ENERGY"
1 TOTAL DECAY ENERGY")
WRITE (6,161)
161 FDSMAT(1T0,7X,(MEV) (MEV),(7X,(MEV/FIS),.12X,(MEV/FIS),.12
1X,(MEV/FIS))")
WRITE(6,162) (J,EI(J),EI(J+1),BET(J),GAM(J),TDT(J),J=1,NGI)
162 FDSMAT(1T0,14,4X,OPF3.1,4X,OPF3.1,6X,1PE13.5,8X,1PE13.5,8X,1PE13.5,8X,1PE13.5,8X,1PE13.5,8X,1PE13.5,8X)
1 )
WRITE(6,164) BTD,BTDT,STDT
164 FDSMAT(1T0," TOTALS OVER GROUPS ",3X,1PE13.5,8X,1PE13.5,8X,
1 1PE13.5)
1 IF(IPLT.EQ.0) GO TO 200
CALL PLOTIT(TDT,1,1)
CALL PLOTIT(BET,2,1)
CALL PLOTIT(GAM,3,1)
200 CONTINUE
IF(IPLT.EQ.0) GO TO 250
CALL DONEPL
CALL GODNE
250 STOP
END
SUBROUTINE REGGROUP(BET,GAM,TOT)
COMMON /VAR/NGI,EI(20),NTSP,T50,UFRAC,TFLUX,ETFLUX,DTIME,UFG,
2 UCFLU,PUFG,PUFB,IPLT,IST
REAL E(20),BET(2),GAM(2),TDT(2),EI(7),E2(13)
REGR 10
END
DATA E/O...1.2.4..6...8.1...2.1.4.1.6.1.8.2.2.2.2.4.
1.2.6.3..4...5..6..7.5/
DATA E1/O...1.2.3..4...5..7.5/
DATA E2/O...4...8.1...1.4.1.8.2.2.2.6.3..4...5..6..7.5/
C SHIFT BETA GROUPS DOWN SO GROUP 1 IS EMPTY
DD 2 I=1,18
1 BET(19-I+1)*BET(19-I)
2 BET(I)=0.
C STANDARD 19 GROUPS
IF(NGI.NE.19) GO TO 5
DD 3 I=1,20
3 EI(I)=E(I)
RETURN
C LOOK FOR STANDARD 6 AND 12 GROUPS
5 IF(NGI.GT.0) GO TO 9
IF(NGI.NE.6) GO TO 7
NGI=6
DD 6 I=1,7
6 EI(I)=EI(I)
GO TO 9
7 NGI=12
DD 8 I=1,13
8 EI(I)=E2(I)
9 NG=20
JSTART=1
DD 100 J=1,NG
10 NGI=19
J=JSTART,NG
10 CONTINUE
RETURN
C FIND HOW MANY GROUPS TO COMBINE
IF(EI(I+1).EQ.E(LJ)) GO TO 20
CONTINUE
WRITE(6,15)
FORMAT("Illegal energy bounds specified")
STOP
20 T1=0.
T2=0.
T3=0.
JEND=J-1
DD 30 K=JSTART,JEND
T1=T1+BET(K)
T2=T2+GAM(K)
T3=T3+TOT(K)
30 BET(I)=T1
GAM(I)=T2
TOT(I)=T3
JSTART=J
CONTINUE
100 CONTINUE
RETURN
END
SUBROUTINE READSUB
COMMON /VAR/NG,NG1,E(I),NGI,E(20),NTSP,T(50),UFRAC,TFLUX,ETFLUX,DTIME,UGF,
2 UFB,PUFG,PUFB,IPLT,IIST
READ *,UFRAC,TFLUX,ETFLUX,DTIME,NGI,NTSP,IPLT,IIST
NGI=NGI+1
IF(NGI.LT.21) GO TO 10
READ 60
WRITE(6,8)
8 FORMAT("Max of 20 groups")
STOP
10 IF(NGI.GT.0) READ *,(EI(I),I=1,NG1)
IF(NGI.EQ.0) NGI=19
IF(NTSP.GT.0) GO TO 30
READ *,TMIN,TMAX
IF(TMIN.LT.TMAX) GO TO 15
NTSP=1
T(I)=TMIN
25
C: TO 40
NTSP=NTSP+1
10 CONTINUE
C: TO 40
NTSP=NTSP+1
STOP
READ *,(T(I),I=1,NTSP)
READ *,UFG,UFB,PUFG,PUFB
RETURN
SUBROUTINE EVAL(NCID,ABCDR)
COMMON /VAR/NGI,EI(20),NTSP,T(50),UFRAC,TFLUX,FUXL,DTIME,UFG,PUFG,PUFB,IPLT,IST
COMMON /ABsp/Oc,YU,YPu,PExs,FEPXS,PTXS,FTXS
REAL ABCOR(2),Li
NCID- NUCLIDE ID 1 FOR CS 2 FOR EU
DC DECAY CONSTANT
YU CUMULATIVE YIELD FRACTION FROM THERMAL FISSION U-235
EPFRS(N,GAM) XS OF PRECURSOR EPITHERMAL
FEPXS(N,GAM) XS OF SECOND NUCLIDE
PTXS(N,GAM) XS OF PRECURSOR THERMAL
FTXS(N,GAM) XS OF SECOND NUCLIDE
K CONSTANT
EVALUATE ADDITIONAL ATOM DENSITY OF NUCLIDE 2 RESULTING
FROM RADIOATIVE CAPTURE IN NUCLIDE 1.
THIS TERM IS INDEPENDENT OF GROUP OR COOLING TIME.
ABCDR(1) FOR U ... ABCDR(2) FOR PU
Y*A*/K(j/(A*B)-(EXP(-A*DTIME)/(A*(13-A)))+(EXP(-B*DTIME)/(B*(B-A))))
A*PTXS*FUXL+PEPSX*FETFLUX
B*=DC*FUXL+PEPSX*FETFLUX*1.E-24
ABCOR(1)*A*K+(1/(A+B))-(EXP(-A*DTIME)/(A*(A-B)))+(EXP(-B*DTIME)/(B*(B-A)))+(EXP(-B*DTIME)/(B*(B-A))))
ABCOR(2)*ABCOR(1)*YU
RETURN
END
SUBROUTINE CSCHN
COMMON /ABsp/X(7)
REAL AR(7)
DATA AR/1.06523E-8..06779.0.06957.34.12.20.454.30.162.140.67/
FILL ABSP COMMON WITH VALUES FOR CS CHAIN
DD 10 I=1,7
10 X(I)=AR(I)
SUBROUTINE EUCHN
COMMON /VAR/ NGI, EI(20), NTSP, T(50), IFRAC, TFLUX, ETFLUX, DTIME, UFG, UFB, PUFG, PUFB, IPLT, IST
COMMON /ABSP/X(7)
C FILL IN ABSP COMMON WITH VALUES FOR EU CHAIN
REAL AR(7)
DATA AR/5.28152E-7, .00033, .00170, 153.59, 129.52, 40.59, .8, 484.94/
00 fO 1=1,7
10 X(I)=AR(I)
C CORRECT CUMULATIVE YIELD
C F IS FLUENCE
F=TFLUX*DTIME*1.E-2
FLOG=ALOG(F)
IF(F.GT.3.0) GO TO 20
Y=EXP(1.688*FLOG-6.565)
GO TO 30
Y=EXP(-0.1827*FLOG**2+1.47*FLOG-6.105)
X(2)=X(2)+Y
X(3)=X(3)+Y
RETURN
END
SUBROUTINE PLDTIT(DT, NT, I)
REAL X(50), Y(50), OT(2)
INTEGER XL(2), YL(5), TL(5)
COMMON /VAR/ NGI, EI(20), NTSP, T(50), UFG, UFB, PUFG, PUFB, IPLT, IST
C MAKE PLOTS OF DECIY ENERGY /BIN vs ENERGY FOR EACH COOLING TIME -
C NT=1 FOR TOTAL BETA +GAMMA
C NT=2 FOR BETA PLOT
C NT=3 FOR GAMMA PLOT
DATA X0, Y0, ENER=10.000, E=<, C0H=E<.
1
100 ENERGY PER . 10H>B<IN >W<1, 10HDTH$
1 IF(NNT.NE.1) GO TO 15
TL(1)=10H T<DTAL> E
TL(2)=10H+<ENERGY FOR
TL(3)=10H >C<DLING
TL(4)=10H> T<IME
ENCDE(9,10,TL(5)) T(I)
10 FORMAT(1PE9.3)
15 IF(NNT.EQ.2) TL(1)=10H B<ETA >E
IF(NNT.EQ.3) TL(1)=10H <G<AAMMA >E
NP=NGI*2
X(1)=EI(1)
K=2
DO 20 J=2, NP, 2
X(J)=EI(K)
X(J+1)=X(J)
20 K=K+1
K=1
DO 30 J=1, NP, 2
Y(J)=DT(K)/(EI(K+1)-EI(K))
IF(Y(J), LE.0.0) Y(J)=1.E-10
Y(J+1)=Y(J)
30 K=K+1
CALL SETUP(X, Y, NP, TL, 50, XL, 100, YL, 100, 0, 0, 0, 2)
CALL ENOPL(0)
RETURN
END
SUBROUTINE STNDRD(AC)
C CALCULATE TOTAL DECIY HEAT USING ANSI/ANS=5.1 STANDARD
COMMON /VAR/ NGI, EI(20), NTSP, T(50), UFRAC, TFLUX, ETFLUX, DTIME, UFG, UFB, PUFG, PUFB, IPLT
RETURN
END
REAL STL(23,2),STA(23.2),ST(50),AC(50,19,2,2)
C U-235 ALPHAS
DATA (STA(I,1),I=1,23)/.65057,.51264,.24384,.13850,.055440,.022225/
DATA (STA(I,2),I=1,23)/.2083,.3853,.2213,.09460,.03536,.02292/
C U-235 LAMBDAS
DATA (STL(I,1),I=1,23)/22.138,.51587,.19594,.10314,.033656,.016880/
DATA (STL(I,2),I=1,23)/10.02,.6433,.2186,.1004,.03728,.01435/
C PU-239 ALPHAS
DATA (STA(I,2),I=1,23)/.2083,.3853,.2213,.09460,.03536,.02292/
DATA (STA(I,1),I=1,23)/.2083,.3853,.2213,.09460,.03536,.02292/
C PU-239 LAMBDAS
DATA (STL(I,2),I=1,23)/10.02,.6433,.2186,.1004,.03728,.01435/
DATA (STL(I,1),I=1,23)/22.138,.51587,.19594,.10314,.033656,.016880/
C STANDARD FOR TOTDALS ONLY
DD 100 I=1,NTSP
ST(I)=0.
DD 90 J=1,2
S=0.
C LDOP THRU URANIUM THEN PLUTONIUM CALC
C SEE IF BURST OR FINITE IRRADIATION CALC
IF(O TIME.NE.0.) GD TO 20
DO 10 K=1,23
S=S+STA(K,1)*EXP(-STL(K,1)*T(I))
GO TO 80
10 S=S+STA(K,2)/STL(K,2)*EXP(-STL(K,2)*T(I))*(1-EXP(-STL(K,2)*OTIME))
C ADO IN ALL ABSORPTION CORRECTIONS
00 30 K=1,2
00 30 L=1,19
S=S+AC(I,L,K) *UFRAC*S
=ST(I)+(1-UFRAC)*S
C FIGURE PER CENT FOR U AND PU
80 IF(J.EQ.1) ST(I)=UFRAC*S
IF(J.EQ.2) ST(I)=ST(I)+(1-UFRAC)*S
90 CONTINUE
100 CONTINUE
C PRINT RESULTS
TEMP1=UFRAC*100.
TEMP=100.-TEMP1
WRITE(6,150)
150 FORMAT(1H1,120,"CALCULATION OF ANSI/ANS-5.1'STANDARD")
WRITE (6,152) TEMP,TEMP,TFUX,ETFLUX,DTIME
152 FORMAT(T30,"PERCENT U-235",T50,1PE11.4/)
1 T30,"PERCENT PU-239",T50,1PE11.4/
2 T30,"THERMAL FLUX",T50,1PE11.4," N/CM"2-S"/
3 T30,"EPITHERMAL FLUX",T50,1PE11.4," N/CM"2-S"/
4 T30,"OPERATING TIME",T50,1PE11.4," SECONDS")
WRITE(6,154)
154 FORMAT(/T10,"COOLDING TIME",T40,"TOTAL DECAY ENERGY/
1 T15,"(SEC)",T45,"(MEV/FIS)"
WRITE(6,155) (T(I),ST(I),I=1,NTSP)
156 FORMAT (T12,1PE12.5,T42,1PE12.5)
STOP
RETURN
END
| DATA (XLPIK(1, 1), K=1, 20)/ | DATA 20 |
| X .6434E-11, .1913E-10, .1578E-09, .2530E-08, .1708E-07, .4206E-07, DATA 40 |
| X .1834E-06, .5005E-06, .2179E-05, .8087E-05, .2306E-04, .9554E-04, DATA 50 |
| X .5491E-03, .1932E-02, .1696E-02, .6758E-03, .6054E-03, .2326E-03, DATA 60 |
| XO, 0, DATA 70 |
| DATA (XLAM(K, 1, 1), K=1, 20)/ | DATA 80 |
| X .7896E-09, .9474E-08, .3256E-07, .1501E-06, .9199E-06, .3307E-05, DATA 90 |
| X .1780E-04, .7042E-04, .1454E-03, .4016E-03, .1345E-02, .7228E-02, DATA 100 |
| X .3939E-01, .1833E-01, .8551E+00, .8562E+00, .4875E+01, .4558E+01, DATA 110 |

```
COMMON /FITS/ XALP(20, 19, 4), XLAM(20, 19, 4), KTRM(19, 4)
```

- `COMMON /FITS/ XALP(20, 19, 4), XLAM(20, 19, 4), KTRM(19, 4)`
<table>
<thead>
<tr>
<th>K</th>
<th>XALP(K,14,1)</th>
<th>XALP(K,15,1)</th>
<th>XALP(K,16,1)</th>
<th>XALP(K,17,1)</th>
<th>XALP(K,18,1)</th>
<th>XALP(K,19,1)</th>
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</thead>
<tbody>
<tr>
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<td>1.7277E-09</td>
<td>2.727E-12</td>
<td>7.098E-09</td>
<td>7.006E-09</td>
<td>1.90934E-15</td>
<td>6.959E-09</td>
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<tr>
<td>2</td>
<td>3.340E-02</td>
<td>4.138E-10</td>
<td>2.872E-11</td>
<td>2.879E-04</td>
<td>5.026E-13</td>
<td>2.317E-06</td>
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<tr>
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<td>3.420E-02</td>
<td>9.505E-03</td>
<td>1.951E-00</td>
<td>1.550E-03</td>
<td>5.935E-08</td>
<td>5.296E-04</td>
</tr>
<tr>
<td>4</td>
<td>2.727E-12</td>
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<td>1.425E-01</td>
<td>1.575E-01</td>
<td>1.599E-01</td>
<td>2.415E-01</td>
</tr>
<tr>
<td>6</td>
<td>9.505E-03</td>
<td>2.441E-02</td>
<td>3.570E-07</td>
<td>3.577E-01</td>
<td>5.296E-04</td>
<td>4.287E-06</td>
</tr>
<tr>
<td>7</td>
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<td>3.577E-01</td>
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<td>7.243E-07</td>
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<td>4.287E-06</td>
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<td>3.570E-07</td>
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<td>4.287E-06</td>
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<td>3.570E-07</td>
<td>3.577E-01</td>
<td>5.296E-04</td>
<td>4.287E-06</td>
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<td>4.287E-06</td>
</tr>
</tbody>
</table>

C FITS FOR U-235 GAMMAS GROUPS 1 THROUGH 19

DATA (XALP(K, 1, 2), K=1, 20)

DATA (XLAM(K, 1, 1), K=1, 20)
<table>
<thead>
<tr>
<th>DATA (XIAM(K, 7, 2), K=1, 20)/</th>
</tr>
</thead>
<tbody>
<tr>
<td>X .7047E-09, .2167E-07, .2207E-07, .3623E-06, .8302E-06, .2815E-05, DATA2560</td>
</tr>
<tr>
<td>X .1497E-04, .2924E-04, .1891E-03, .1162E-02, .2700E-01, DATA2570</td>
</tr>
<tr>
<td>X .1068E+00, .4804E+00, .1129E+01, .2848E+01, .4440E+01, .0, DATA2590</td>
</tr>
<tr>
<td>XO. / DATA2600</td>
</tr>
<tr>
<td>DATA (XALP(K, 8, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2433E-16, .3457E-13, .1720E-12, .3215E-10, DATA2610</td>
</tr>
<tr>
<td>X .8842E-07, .3422E-05, .1351E-04, .1040E-03, .2014E-02, .7000E-02, DATA2630</td>
</tr>
<tr>
<td>X .1128E+00, .3390E-01, .5434E+00, .5846E+00, .1887E-03, .0, DATA2640</td>
</tr>
<tr>
<td>XO. / DATA2660</td>
</tr>
<tr>
<td>DATA (XLAM(K, 8, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2433E-16, .3457E-13, .1720E-12, .3215E-10, DATA2610</td>
</tr>
<tr>
<td>X .8842E-07, .3422E-05, .1351E-04, .1040E-03, .2014E-02, .7000E-02, DATA2630</td>
</tr>
<tr>
<td>X .1128E+00, .3390E-01, .5434E+00, .5846E+00, .1887E-03, .0, DATA2640</td>
</tr>
<tr>
<td>XO. / DATA2660</td>
</tr>
<tr>
<td>DATA (XALP(K, 9, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2657E-17, .4743E-11, .2442E-11, .1499E-06, .1019E-04, .1913E-03, DATA2710</td>
</tr>
<tr>
<td>X .1784E-02, .8929E-02, .1433E-01, .6409E-02, .8391E-02, .2153E-02, DATA2730</td>
</tr>
<tr>
<td>X .1150E-03, .2028E-06, .1274E-06, .9048E-06, .7048E-06, .0, DATA2740</td>
</tr>
<tr>
<td>XO. / DATA2750</td>
</tr>
<tr>
<td>DATA (XLAM(K, 9, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2433E-16, .3457E-13, .1720E-12, .3215E-10, DATA2610</td>
</tr>
<tr>
<td>X .8842E-07, .3422E-05, .1351E-04, .1040E-03, .2014E-02, .7000E-02, DATA2630</td>
</tr>
<tr>
<td>X .1128E+00, .3390E-01, .5434E+00, .5846E+00, .1887E-03, .0, DATA2640</td>
</tr>
<tr>
<td>XO. / DATA2660</td>
</tr>
<tr>
<td>DATA (XALP(K, 10, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2671E-18, .1056E-12, .4417E-13, .1072E-11, .1159E-08, .1388E-08, DATA2810</td>
</tr>
<tr>
<td>X .4823E-06, .3281E-05, .1291E-04, .4864E-03, .3784E-02, .1598E-01, DATA2830</td>
</tr>
<tr>
<td>X .1520E+00, .1049E+00, .2377E+00, .8004E-05, .2568E+00, .0, DATA2790</td>
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<tr>
<td>XO. / DATA2850</td>
</tr>
<tr>
<td>DATA (XLAM(K, 10, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2671E-18, .1056E-12, .4417E-13, .1072E-11, .1159E-08, .1388E-08, DATA2810</td>
</tr>
<tr>
<td>X .4823E-06, .3281E-05, .1291E-04, .4864E-03, .3784E-02, .1598E-01, DATA2830</td>
</tr>
<tr>
<td>X .1520E+00, .1049E+00, .2377E+00, .8004E-05, .2568E+00, .0, DATA2790</td>
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<tr>
<td>XO. / DATA2850</td>
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<tr>
<td>DATA (XALP(K, 11, 2), K=1, 20)/</td>
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<tr>
<td>X .2024E-18, .5844E-13, .6540E-10, .1507E-08, .2069E-08, .2169E-07, DATA2910</td>
</tr>
<tr>
<td>X .2723E-06, .2706E-05, .1521E-04, .5338E-04, .1569E-03, .6287E-03, DATA2930</td>
</tr>
<tr>
<td>X .1160E-02, .6638E-02, .1869E-01, .2948E-01, .0, .0, .0, DATA2940</td>
</tr>
<tr>
<td>XO. / DATA2950</td>
</tr>
<tr>
<td>DATA (XLAM(K, 11, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2024E-18, .5844E-13, .6540E-10, .1507E-08, .2069E-08, .2169E-07, DATA2910</td>
</tr>
<tr>
<td>X .2723E-06, .2706E-05, .1521E-04, .5338E-04, .1569E-03, .6287E-03, DATA2930</td>
</tr>
<tr>
<td>X .1160E-02, .6638E-02, .1869E-01, .2948E-01, .0, .0, .0, DATA2940</td>
</tr>
<tr>
<td>XO. / DATA2950</td>
</tr>
<tr>
<td>DATA (XALP(K, 12, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2671E-12, .3418E-10, .2568E-08, .3248E-09, .3676E-06, .2663E-05, DATA3010</td>
</tr>
<tr>
<td>X .2568E-04, .8103E-04, .1192E-02, .4033E-02, .8927E-02, .1476E+00, DATA3030</td>
</tr>
<tr>
<td>X .1415E+00, .1026E-10, .0, .0, .0, .0, .0, DATA3040</td>
</tr>
<tr>
<td>XO. / DATA3050</td>
</tr>
<tr>
<td>DATA (XLAM(K, 12, 2), K=1, 20)/</td>
</tr>
<tr>
<td>X .2671E-12, .3418E-10, .2568E-08, .3248E-09, .3676E-06, .2663E-05, DATA3010</td>
</tr>
<tr>
<td>X .2568E-04, .8103E-04, .1192E-02, .4033E-02, .8927E-02, .1476E+00, DATA3030</td>
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<tr>
<td>X .1415E+00, .1026E-10, .0, .0, .0, .0, .0, DATA3040</td>
</tr>
<tr>
<td>XO. / DATA3050</td>
</tr>
<tr>
<td>DATA (XALP(K, 13, 2), K=1, 20)/</td>
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<tr>
<td>X .8784E-13, .1050E-16, .1016E-15, .4116E-11, .9380E-09, .4627E-09, DATA3110</td>
</tr>
<tr>
<td>X .1670E-06, .2679E-05, .1391E-04, .6762E-04, .1035E-02, .5141E-02, DATA3130</td>
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<td>X .1035E+00, .2306E-01, .1034E+00, .0, .0, .0, .0, DATA3140</td>
</tr>
<tr>
<td>XO. / DATA3150</td>
</tr>
<tr>
<td>DATA (XLAM(K, 13, 2), K=1, 20)/</td>
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<tr>
<td>X .2174E-07, .1898E-07, .3614E-06, .4137E-06, .6352E-06, .2476E-05, DATA3170</td>
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<tr>
<td>X .4117E-04, .8088E-04, .3708E-03, .2403E-02, .1483E-01, .1085E+00, DATA3180</td>
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<tr>
<td>X .1296E+01, .3206E+01, .1609E+01, .0, .0, .0, .0, DATA3190</td>
</tr>
<tr>
<td>K</td>
</tr>
<tr>
<td>-----</td>
</tr>
</tbody>
</table>

C FITS FOR PU-239 BETAS GROUPS 1 AND 2 COMBINED INTO 1

DATA (XALP(K, 1, 3), K=1, 20)

<table>
<thead>
<tr>
<th>K</th>
<th>X1</th>
<th>X2</th>
<th>X3</th>
<th>X4</th>
<th>X5</th>
<th>X6</th>
<th>X7</th>
<th>X8</th>
<th>X9</th>
<th>X10</th>
<th>X11</th>
<th>X12</th>
<th>X13</th>
<th>X14</th>
<th>X15</th>
<th>X16</th>
<th>X17</th>
<th>X18</th>
<th>X19</th>
<th>X20</th>
</tr>
</thead>
</table>

C FITS FOR PU-239 BETAS GROUPS 1 AND 2 COMBINED INTO 1
### Fits for Pu-239 Gammas Groups 1 Through 19

#### Data (XALP(K,1,4),K=1,20)

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<th>(0.1672E-04)</th>
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<th>(0.1452E-01)</th>
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<tr>
<td>(0.2618E-01)</td>
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<td>(0.1672E-04)</td>
<td>(0.6538E-04)</td>
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<td>(0.4199E-04)</td>
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<td>(0.1284E-02)</td>
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<tr>
<td>(0.4199E-04)</td>
<td>(0.5579E-03)</td>
<td>(0.1284E-02)</td>
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#### Data (XALP(K,15,3),K=1,20)

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<th>(0.8334E-11)</th>
<th>(0.2808E-10)</th>
<th>(0.1693E-09)</th>
<th>(0.6576E-08)</th>
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<tr>
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<td>(0.9686E-07)</td>
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<td>(0.5535E-03)</td>
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#### Data (XALP(K,16,3),K=1,20)

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<th>(0.8334E-11)</th>
<th>(0.2808E-10)</th>
<th>(0.1693E-09)</th>
<th>(0.6576E-08)</th>
</tr>
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<td>(0.9686E-07)</td>
<td>(0.2722E-06)</td>
<td>(0.3451E-05)</td>
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<td>(0.5192E-04)</td>
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<td>(0.1414E-02)</td>
<td>(0.7911E-02)</td>
<td>(0.3107E-01)</td>
<td>(0.5802E-01)</td>
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<tr>
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<td>(0.1432E+01)</td>
<td>(0.6153E+00)</td>
<td>(0.2640E+01)</td>
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#### Data (XALP(K,17,3),K=1,20)

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C FITS FOR PU-239 GAMMAS GROUPS 1 THROUGH 19

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CALL BGNPL (-1)
CALL NOBRDR
CALL PAGE (XPAGE,YPAGE)
XG=XPAGE-1.7
YG=YPAGE-1.7
HITE=.03*YG
CALL HITE (.03)
CALL SCMPLX
CALL MXIALF(5HSTAND,1H>)
CALL MX2ALF(5HL/CST,1H>)
CALL MX3ALF(5HINSTR,1H#)
XLEFT=XRIGHT=X1(1)
YTOP=YBOT=Y1(1)
DO 5 I=2,L1
1) IF(X1(I).LT.XLEFT) XLEFT=X1(I)
2) IF(X1(I).GT.XRIGHT) XRIGHT=X1(I)
3) IF(Y1(I).LT.YBOT) YBOT=Y1(I)
4) IF(Y1(I).GT.YTOP) YTOP=Y1(I)
5) CONTINUE
IF(IYTYPE.LT.3) GO TO 6
TOP=ALOGIO(XRIGHT)
IF(TOP.GE.0.) XRIGHT=10.**IFIX(TOP+.99)
IF(TOP.LT.0.) XRIGHT=10.**IFIX(TOP)
IF(XLEFT.NE.0.) GD TO 6
XLEFT=10.**IFIX(TOP-.15.)
6) IF(IYTYPE.NE.2.AND.IYTYPE.NE.4) GD TO 7
TOP=ALOGIO(YTOP)
IF(TOP.GE.0.) YTOP=10.**IFIX(TOP+.99)
IF(TOP.LT.0.) YTOP=10.**IFIX(TOP)
IF(YBOT.GT.0.) GD TO 7
YBOT=10.**IFIX(TOP-.15.)
7) IF (IYTYPE.NE.1) GD TO 10
CALL AXSPLT (YBOT,YTOP,YG,YORIG,YSTEP,YAXIS)
YPD=IFIX((YPD+YSTEP)/YSTEP)*YSTEP
CALL AXSPLT (XLEFT,XRIGHT,XPAGE,YPAGE)
CALL TITLE (0.0,0.0,XL,NX,YL,NY,XG,YG)
CALL GRAF (XORIG,XSTEP,XRIGHT,YORIG,YSTEP,YTOP)
GO TO 40
10) IF (IYTYPE.NE.2) GD TO 20
CALL AXSPLT (XLEFT,XRIGHT,XPAGE,YPAGE)
XRIGHT=IFIX((XRIGHT+XSTEP)/XSTEP)*XSTEP
CALL AXSPLT (0.0,0.0,YL,NY,XG,YG)
CALL XLOG (XORIG,XCYCLE,0.1)
CALL XRAXS (XORIG,XCYCLE,XRIGHT,0.1)
CALL YLOG (0.0,YORIG,YCYCLE)
CALL YGAXS (XORIG,YORIG,YCYCLE)
CALL FRAME
IF(IGRD.EQ.1) CALL GRID(1,1)
IF(IGRD.NE.2) GD TO 41
CALL BLNK1(.13,XG,-.13,0.,YG,0)
CALL GRID(0.1)
CALL BBLNK(1)
CALL BLNK1(.13,XG,.13,0.,YG,0)
CALL GRID(1.0)
CALL BBLNK(1)
41) IF(IYCON.NE.0) CALL MARKER(1M)
CALL CURVE (X1,Y1,L1,ICON)
CALL CURVE (X1,Y1,L1,ICON)
CALL NUM (NT,GX,YG,1.1)
RETURN
**SAMPLE PROBLEM INPUT**

1. E+14, 5. E+14, 7.2E+7, -12.2, 0.0

**SAMPLE PROBLEM OUTPUT**

### FISSION PRODUCT DECAY ENERGY FOR A MIXTURE OF U-235 AND PU-239

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**TOTALS OVER GROUPS**

| 2.02953E-01 | 2.55891E-01 | 4.58844E-01 |

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### FISSION PRODUCT DECAY ENERGY FOR A MIXTURE OF U-235 AND PU-239

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**TOTALS OVER GROUPS**

| 9.71198E-03 | 8.32299E-03 | 1.80350E-02 |
APPENDIX B

ACCURACY ESTIMATE OF ADJUSTED SPECTRAL FITS

As an aid in estimating the accuracy of the adjusted spectral fits, calculations made with the adjusted fits were separately compared to both aggregate spectral summation results calculated using the CINDER code and ENDF/B-V data and also with the experimental results. Examples of these comparisons are shown graphically in Figs. B-1 through B-5 for the aggregate gamma-ray decay energy from fission products resulting from a pulse irradiation (1 x 10^{-4} s) of $^{239}$Pu with thermal neutrons. (Note that although in figures comparing calculated decay energies with experiment, the experimental points have been reduced to a pulse; those figures showing the deviations take into consideration the actual irradiation times used in the experiments.) The comparisons shown in these figures are for a low-energy group (0.1-0.2 MeV) in Fig. B-1, for two intermediate-energy groups (0.8-1.0 MeV and 1.4-1.6 MeV) in Figs. B-2 and B-3, respectively, and two high-energy groups (2.2-2.4 MeV and 4.0-5.0 MeV) in Figs. B-4 and B-5, respectively. As demonstrated by these figures, the adjusted fits most closely follow the experimental data in the cooling-time range of the experiments, the ENDF/B-V aggregate data for cooling times greater than the range of the experiments, and are extrapolations of the experimental data with ENDF/B-V "shape" for very early cooling times. Note, however, as can be seen in Fig. B-4, that for high beta- and gamma-ray energies, and for long cooling times, the dispersion of the experimental data is so great that the adjusted fits have been forced to fit the ENDF/B-V aggregate data. Also, for the highest energy group (6.0-7.5 MeV), no experimental data were available and the adjusted fits are entirely ENDF/B-V.

As a first step in estimating the reliability of the adjusted fits, we divide the cooling-time range into bins having widths of one decade, except that the last bin is understood to extend to the end of the cooling-time range (1 x 10^{9} s). Averages of deviations of points calculated using the adjusted fits from the aggregate ENDF/B-V pulse points and from the experimental points are next tabulated separately for each energy group and cooling-time decade for the aggregate betas and gammas from each fissioning nuclide ($^{235}$U and $^{239}$Pu) as shown in Tables B-I through B-IV. Combined "accuracy" estimates are then made as follows.
For cooling times less than 1 s (i.e., below the experimental range), the combined estimate is taken to be one-half the average deviation for ENDF/B-V.

For cooling times in the range of $1 \text{s} - 1 \times 10^4 \text{s}$, where it is believed that the experimental data are the most accurate, the combined estimate is taken as one-fourth the absolute value of the average deviation for ENDF/B-V plus the average deviation for the experiment.

For cooling times above $1.0 \times 10^4 \text{s}$, but within the range of the experiments, it is assumed that ENDF/B-V data are as valid as the experimental data so the combined estimate is the absolute value of the average deviation for ENDF/B-V plus the absolute value of the experimental deviation. Exceptions to this are the highest energy groups for which the deviations for the experimental data are essentially ignored above 1000 s. (See Fig. B-4.)

For cooling times above the experimental range, the combined estimate is just the absolute value of the average deviations from the ENDF/B-V data, as the adjusted fits in this time domain are just fits to the aggregate ENDF/B-V pulse data.

The minimum combined estimate is taken to be 5%, as this is judged to be the "accuracy" of the ENDF/B-V fits, i.e., no point calculated with the ENDF/B-V fits deviates more than 5% from an aggregate ENDF/B-V data point.

The multigroup energy can be rebinned into broader groups for purposes of making uncertainty estimates, as it is generally noted that the experimental gamma-ray decay energy data are lower than the aggregate summation calculations using ENDF/B-V data for low energies, are in fair agreement for intermediate energies, and are high for high energies. (The opposite is more or less the case for the betas.) Similarly, wider cooling-time bins can also be assigned.

In accordance with the above, absolute averages of the average deviations were taken over four energy and four cooling-time ranges. The results are displayed in Tables B-V through B-VIII, which also give the bounds of energy and cooling-time ranges as well as the absolute averages of the deviations.

First, note in comparing Tables B-V through B-VIII that the deviations for the gammas are generally higher than those for the betas. This is not surprising since only one experiment (the ORNL) was included in obtaining the adjusted
beta fits. The deviations in Table B-V and B-VII, therefore, are considered somewhat optimistic.

On the other hand, the large deviations seen in Tables B-VI and B-VIII for the gammas for short cooling times and high energies seem overly pessimistic when examining the numbers in Tables B-II and B-IV. Note in these latter tables that the adjusted fits are extrapolations of closely followed experimental data. As discussed in Ref. 6, we believe that the experimental data are correct for this energy-cooling time domain, and that the data in the ENDF/B-V file are deficient for those nuclides contributing to the decay energy in this domain.

Because of the foregoing, it does not seem unreasonable to make a single estimate of "one-sigma" uncertainties for the adjusted fits for both the beta- and gamma-ray decay energies resulting from the thermal pulse irradiation of both $^{235}\text{U}$ and $^{239}\text{Pu}$. This is done by taking simple averages of the deviations in each energy and cooling-time range in Tables B-V through B-VIII. The resulting table appears in Sec. V of the main body of this report. Note that a user may be dissatisfied with the final result of this analysis and may wish to reestimate the uncertainties according to his own needs. If so, Tables B-I through B-IV are available for this task.
Comparison with ENDF/B-V aggregate data.

Comparison with experimental data.

Fig. B-1. Comparisons of adjusted fits for Group 2 (0.1-0.2 MeV)
Comparison with ENDF/B-V aggregate data.

Comparison with experimental data.

Fig. B-2. Comparisons of adjusted fits for Group 6 (0.8-1.0 MeV).
Comparison with ENDF/B-V aggregate data.

Comparison with experimental data.

Fig. B-3. Comparisons of adjusted fits for Group 9 (1.4-1.6 MeV).
Comparison with ENDF/B-V aggregate data.

Fig. B-4. Comparisons of adjusted fits for Group 13 (2.1-1.4 MeV).
Comparison with ENDF/B-V aggregate data.

Comparison with experimental data.

Fig. B-5. Comparisons of adjusted fits for Group 17 (4.0-5.0 MeV).
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<th>COOL TIME DECADE</th>
<th>GROUP 1 ENDF EXP</th>
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<th>GROUP 2 EXP</th>
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<th>GROUP 8 EXP</th>
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**TABLE B-I**

AVERAGE PERCENT DEVIATIONS OF ADJUSTED FITS FROM ENDF/B-V AND EXPERIMENTAL DATA FOR U-235 BETAS
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<th>Cool Time Decade</th>
<th>Group 1 ENDF Exp</th>
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<th>Group 5 ENDF Exp</th>
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<th>Group 7 ENDF Exp</th>
<th>Group 8 ENDF Exp</th>
<th>Group 9 ENDF Exp</th>
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<td>-1.4 0.0 -39.4 0.0 -67.9 0.0 -7.6 0.0 -40.0 0.0 .7 0.0 80.6 0.0 -1.6 0.0 -.1 0.0</td>
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<td>1E+00 - 1E+01</td>
<td>14.1 0.0 -35.9 0.0 -63.6 0.0 -12.2 0.0 -42.9 0.0 .1 0.0 58.7 0.0 -8.4 0.0 -.3 0.0</td>
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<tr>
<td>1E+01 - 1E+02</td>
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<td>1E+02 - 1E+03</td>
<td>-25.2 -.3 -11.5 .0 -37.4 .0 -9.5 -.2 -37.5 -.6 -1.1 -.1 43.4 -1.3 9.3 -.9 7.2 .0</td>
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<td>1E+04 - 1E+05</td>
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<td>1E+06 - 1E+07</td>
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**Table B-II**

**Average Percent Deviations of Adjusted Fits from ENDF/B-V and Experimental Data for U-235 Gammas**
<table>
<thead>
<tr>
<th>COOL TIME DECADE</th>
<th>GROUP 1</th>
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<th>GROUP 3</th>
<th>GROUP 4</th>
<th>GROUP 5</th>
<th>GROUP 6</th>
<th>GROUP 7</th>
<th>GROUP 8</th>
<th>GROUP 9</th>
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<tr>
<td>.1E-01-.1E+00</td>
<td>15.4</td>
<td>51.6</td>
<td>28.5</td>
<td>-1.7</td>
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<td>-0.2</td>
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<td>.1E+00-.1E+01</td>
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<td>4.8</td>
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<td>-0.4</td>
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<td>.1E+01-.1E+02</td>
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<td>70.2</td>
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<td>23.3</td>
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<td>-0.4</td>
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<th>GROUP 11</th>
<th>GROUP 12</th>
<th>GROUP 13</th>
<th>GROUP 14</th>
<th>GROUP 15</th>
<th>GROUP 16</th>
<th>GROUP 17</th>
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<td>GROUP 1 EXP</td>
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<td>1E+05-.1E+06</td>
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**TABLE B-IV**

**AVERAGE PERCENT DEVIATIONS OF ADJUSTED FITS FROM ENDF/B-V AND EXPERIMENTAL DATA FOR PU-239 GAMMAS**
TABLE B-V

PERCENT ESTIMATE OF ACCURACY OF ADJUSTED FITS FOR U-235 BETAS

<table>
<thead>
<tr>
<th>ENERGY RANGES (MEV)</th>
<th>COOLING TIME RANGES (S)</th>
<th>1.0E-02-1.0E+00</th>
<th>1.0E+00-1.0E+04</th>
<th>1.0E+04-1.0E+06</th>
<th>1.0E+06-1.0E+09</th>
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<tbody>
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TABLE B-VI

PERCENT ESTIMATE OF ACCURACY OF ADJUSTED FITS FOR U-235 GAMMAS

<table>
<thead>
<tr>
<th>ENERGY RANGES (MEV)</th>
<th>COOLING TIME RANGES (S)</th>
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<th>1.0E+00-1.0E+04</th>
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<th>1.0E+06-1.0E+09</th>
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</thead>
<tbody>
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<td>15.1</td>
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<td>10.9</td>
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<td>11.8</td>
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<tr>
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<tr>
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TABLE B-VII

PERCENT ESTIMATE OF ACCURACY OF ADJUSTED FITS FOR PU-239 BETAS

<table>
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<th>ENERGY RANGES (MEV)</th>
<th>COOLING TIME RANGES (S)</th>
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<th>1.0E+00-1.0E+04</th>
<th>1.0E+04-1.0E+06</th>
<th>1.0E+06-1.0E+09</th>
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</thead>
<tbody>
<tr>
<td>0.0-0.6</td>
<td>18.2</td>
<td>26.7</td>
<td>7.4</td>
<td>5.0</td>
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<td>0.6-1.6</td>
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<td>5.0</td>
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TABLE B-VIII

PERCENT ESTIMATE OF ACCURACY OF ADJUSTED FITS FOR PU-239 GAMMAS

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<tr>
<th>ENERGY RANGES (MEV)</th>
<th>COOLING TIME RANGES (S)</th>
<th>1.0E-02-1.0E+00</th>
<th>1.0E+00-1.0E+04</th>
<th>1.0E+04-1.0E+06</th>
<th>1.0E+06-1.0E+09</th>
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Printed in the United States of America
Available from
National Technical Information Service
US Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Microfiche (A01)

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<td>A19</td>
<td>576-600</td>
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*Contact NTIS for a price quote.