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FEW-GROUP REPRESENTATION OF THE ENERGY SPECTRA OF DELAYED NEUTRONS

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The importance of delayed neutrons in reactor calculations has been well established.[1,2,3,4] A recent evaluation of delayed neutron data has resulted in the compilation of a reference library (described in a companion paper[5]) containing emission probabilities, Pn's, and energy spectra for ~ 272 individual precursor nuclides.[6] The library may be used to calculate aggregate spectra and total delayed neutron yields for various fissioning systems by applying the summation techniques described in Ref. 7.

It is common practice in reactor calculations to use a few-temporal group (e.g., six) representation of delayed neutron data. The above mentioned library has been analyzed in terms of group yields and halflives for three-, six-, nine-, and twelve-delayed neutron groups.[6,8] However, the few-group representation cannot be considered complete until the energy spectra are represented in a consistent manner. The purpose of this paper is to present the method and results of the few-group analysis of the energy spectra.

Delayed neutron activity following a fission pulse may be represented mathematically as a sum of exponentials,

$$n_d(t) = \sum_{i=1}^{N} A_i e^{-\lambda_i t} \quad . \qquad (1)$$

The quantity N represents the total number of temporal groups being considered; A_i, the delayed neutron yield per fission per second for group i; and λ_i, the decay constant for group i. Values for A_i and λ_i are determined from a least-squares analysis.[8] Table I is a comparison of the six-group decay constants and normalized yields for ^{235}U fast and thermal fission.

The physical representation using the individual fission product precursor data is (ignoring coupling)

$$n_d(t) = \sum_{j=1}^{272} \lambda_j \, Pn_j \, YI_j \, e^{-\lambda_j t} \quad , \qquad (2)$$

where YI_j is the direct fission yield and λ_j is the decay constant of nuclide j.

Both Eqs. (1) and (2) describe the delayed neutron activity per fission following a pulse. In the present evaluation, it is required that

$$A_i e^{-\lambda_i t} = \sum_k f_{k,i} \, \lambda_k \, Pn_k \, YI_k \, e^{-\lambda_k t} \quad , \qquad (3)$$

where the subscript i represents mathematical group i, the summation is over all precursors contributing to group i, and $f_{k,i}$ is the fraction of delayed neutrons produced by precursor k that contribute to group i. It is assumed that the fission product precursor may contribute to either or both of the adjacent mathematical groups determined by the decay constants. The sum of $f_{k,i}$ for any k must be unity because $f_{k,i}$ is defined as a fraction. These fractions were determined by requiring the least squares error

$$\int_0^\infty \left\{ \lambda_k e^{-\lambda_k t} - \left[f_{k,i} \lambda_i \, e^{-\lambda_i t} + \left(1 - f_{k,i} \right) \lambda_{i+1} e^{-\lambda_{i+1} t} \right] \right\}^2 dt \qquad (4)$$

to be a minimum.[9] A modification of Newton's method was used to return the minimum of Eq. (4). The equilibrium group spectra were then found as

$$\Phi_i(E) = \sum_k f_{k,i} \, YC_k \, Pn_k \, \Phi_k(E) \quad , \qquad (5)$$

where $\phi_k(E)$ is the delayed neutron spectrum of precursor k.

The ENDF/B-V evaluation for delayed neutrons contains group sepctra for ^{235}U, ^{238}U, and ^{239}Pu. The ^{235}U spectra are used for ^{232}Th and ^{233}U, and the ^{239}Pu spectra are used for ^{240}Pu and ^{241}Pu. For ^{235}U and ^{239}Pu, the Group 4 spectrum is substituted for the Group 5 and Group 6 spectra. In the case of ^{238}U, the Group 5 is also used for Group 6. The spectra are assumed to be independent of incident neutron energy and originally extended from ~ 79 keV to ~ 1.2 MeV. The ENDF/B-V reviewers used a straight line extension from the value at the lower cutoff to the origin and recommended that the low energy spectrum be resolved later.[7]

The normalized six-group spectra for ^{235}U fast and thermal fission are given in Figs. 1(a)-1(f) over a 1-MeV energy range in comparison with the six-group spectra taken from ENDF/B-V for ^{235}U. Differences between our thermal and fast spectra are much less than those with the ENDF/B-V evaluation. This suggests that the dependence on incident neutron energy is small and agrees with earlier results that showed a lack of energy dependence for total delayed neutron spectra.[10] All spectra are normalized such that the integral over the entire energy range is 1.0.

Using the method outlined above, the group-one spectrum shown in Fig. 1(a) has three contributing precursor nuclides. The precursor ^{87}Br contributes 100% of its delayed neutrons to group one, as is expected; however, two additional precursors, ^{137}I and ^{141}Cs contribute about 20% of their delayed neutrons to group one. This result allows the group-one spectrum to change for different fissioning systems, as suggested by ENDF/B-V data.

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TABLE I

Comparison of Six-Group Parameters for ^{235}U

	ENDF/B-V		FITTED VALUES[8]			
			thermal fission		fast fission	
group i	a_i	λ_i	a_i	λ_i	a_i	λ_i
1	0.038	0.0127	0.0377	0.0133	0.0350	0.0133
2	0.212	0.0317	0.1907	0.0325	0.1803	0.0328
3	0.188	0.116	0.1692	0.1224	0.1782	0.1219
4	0.407	0.311	0.3407	0.3170	0.3859	0.3054
5	0.128	1.40	0.1734	0.9900	0.1557	0.8649
6	0.026	3.87	0.0883	2.9573	0.0649	2.8776

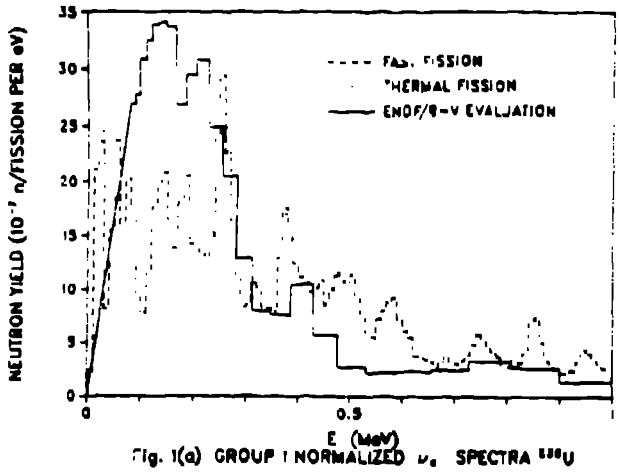

Fig. 1(a) GROUP 1 NORMALIZED ν_d SPECTRA ^{235}U

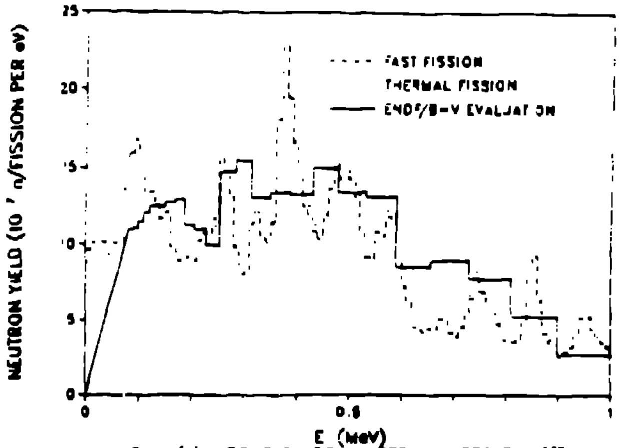

Fig. 1(b) GROUP 2 NORMALIZED ν_d SPECTRA ^{235}U

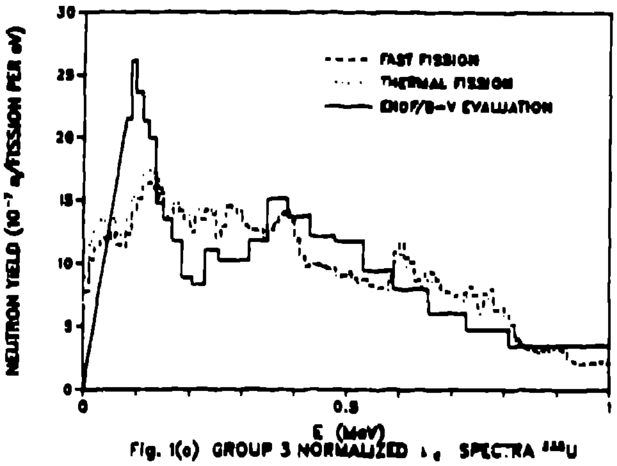

Fig. 1(c) GROUP 3 NORMALIZED ν_d SPECTRA ^{235}U

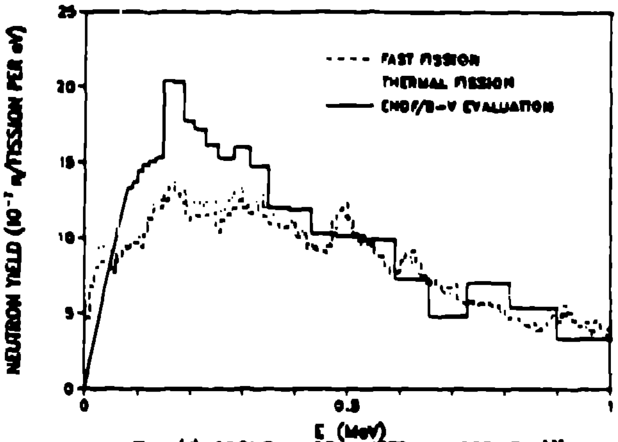

Fig. 1(d) GROUP 4 NORMALIZED ν_d SPECTRA ^{235}U

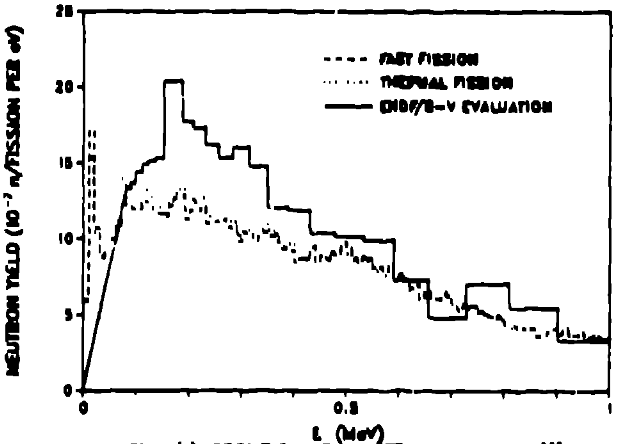

Fig. 1(e) GROUP 5 NORMALIZED ν_d SPECTRA ^{235}U

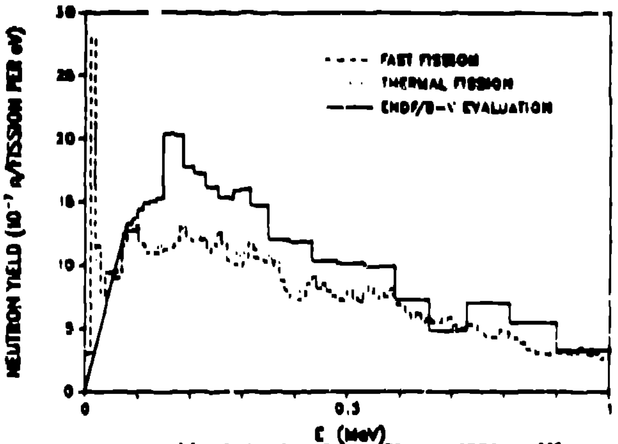

Fig. 1(f) GROUP 6 NORMALIZED ν_d SPECTRA ^{235}U