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A CRITICAL REVIEW OF THE ENERGY RELEASED IN NUCLEAR FISSION

J. P. Unik and J. E. Gindler

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Chemistry

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Chemistry Division

March 1971

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ABSTRACT

This report presents calculations of the total energy released during and following the fission of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, and ^{242}Pu by neutrons of various energies. Two independent methods of calculation are used. The first method is based on the fact that the total energy released in fission is equal to the difference in energy-equivalent masses of the reactants (target nuclide plus neutron) and the stable fission products. The second method involves the summation of all individual contributions to the total energy release. The total energy absorbed in a reactor (the total energy released as a result of fission minus the antineutrino energy plus the energy released by capture of the fission neutrons in the reactor materials and the subsequent decay of the capture products) is estimated for a particular EBR-II-type reactor. Estimates are also made for the dependence of the total energy releases as a function of neutron energy. The limitations of these calculations and estimates as well as deficiencies in available data are discussed in detail.

1. INTRODUCTION

As a result of the fission process, two excited fission fragments are formed which emit neutrons and gamma-rays within a very short time.* The deexcited fragments, or primary fission products as they are commonly called, then undergo radioactive decay, emitting beta particles, antineutrinos, more gamma rays, and X rays, and occasionally a delayed neutron. The total energy released directly from each fission event is the sum of the kinetic energies of the fission fragments E_K, neutrons E_n, gamma rays and X rays E_γ, beta particles E_β, and antineutrinos $E_{\overline{\nu}}$. To distinguish between those neutrons and gamma rays emitted during the deexcitation of the fission fragments from those emitted following β decay of the

*Occasionally, other light particles such as alpha particles, tritons, etc., may be emitted or more than two fragments may result. The probability of occurrence for these events is quite low and is not considered in the present report.

NOTE: The literature search for this report was completed in October 1970.

fission products, we consider the former to be prompt processes and the latter delayed processes and designate the energies with the appropriate subscript, p or d; i.e.

$$E_\gamma = E_{\gamma p} + E_{\gamma d} \tag{1}$$

and

$$E_n = E_{np} + E_{nd}. \tag{2}$$

For a statistically large number of fission events, the average total energy Q_f directly released per fission is the sum of the average energies for each deexcitation mode:

$$Q_f = \overline{E}_K + \overline{E}_{np} + \overline{E}_{\gamma p} + \overline{E}_\beta + \overline{E}_{nd} + \overline{E}_{\gamma d} + \overline{E}_{\overline{\nu}}. \tag{3}$$

The accuracy to which Q_f can be determined by means of Eq. 3 depends on the accuracy to which each component energy can be measured.

Thermodynamically, the energy released by fission is equal to the energy equivalent masses of the reactants minus the sum of the energy-equivalent masses of the products:

$$Q_f = M(A,Z) + M_n + E_i - \sum_i Y_i M(A_i,Z_i) - \overline{\nu}_T M_n, \tag{4}$$

where $M(A,Z)$ is the atomic mass in MeV of the fissionable target nucleus with mass number A and charge Z, M_n and E_i are, respectively, the energy-equivalent mass and incident energy of the neutron, Y_i is the yield of the stable fission product (A_i,Z_i), and $\overline{\nu}_T$ (not to be confused with the antineutrino symbol) is the average total number of neutrons emitted per fission ($\overline{\nu}_T = \overline{\nu}_p + \overline{\nu}_d$).

If $m(A,Z)$ denotes the mass excess in MeV,

$$m(A,Z) = M(A,Z) - Am_0, \tag{5}$$

where m_0 is the rest energy of one atomic mass unit, then Eq. 4 may be rewritten

$$Q_f = m(A,Z) + E_i - \sum_i Y_i m(A_i,Z_i) - (\overline{\nu}_T - 1)\, m_n, \tag{6}$$

where m_n is the neutron mass excess. The accuracy of Q_f obtained by means of Eq. 6 is very good. Masses and therefore mass excesses of the fissioning nuclides and the stable fission products have been determined accurately by mass spectrometry (generally to the order of 20 keV). Since the mass excesses of the stable fission products formed with large yields

are relatively constant and the mass yield distributions for different fissioning systems considered here are rather similar, as shown in Fig. 1, errors in the determination of radiochemical yields do not greatly influence the summation $\sum_i Y_i m(A_i, Z_i)$. Only the mass distributions for ^{232}Th and ^{241}Pu are shown in Fig. 1. These two mass distributions represent the extremes for the fissioning systems considered in this work. Note that Eq. 6 does not permit calculation of the individual component energies summed in Eq. 3. The energies of these individual components are important to reactor design because of the manner in which each component is absorbed by the different reactor materials.

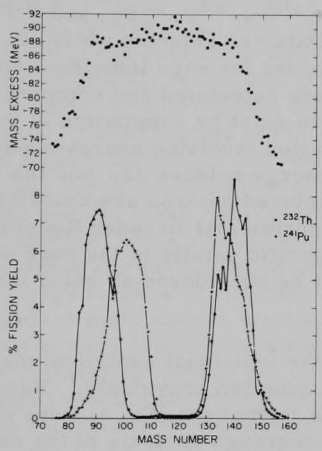

Fig. 1

Mass Excesses for the Stable Isotopes with the Lowest Nuclear Charge for a Given Mass Number A (top: Ref. 10); Radiochemical Mass Yield Distributions for Fast-neutron Fission of ^{232}Th (Ref. 13) and Thermal Fission of ^{241}Pu (bottom: Ref. 11). ANL Neg. No. 121-7164.

In a critical reactor, one neutron of energy E_i is required to perpetuate the chain reaction. This reduces the average total energy released directly in the fission process to the net value

$$Q_f' = Q_f - E_i. \tag{7}$$

The effective average total energy absorbed in the reactor is reduced from the value Q_f' by the amount $\overline{E}_{\overline{\nu}}$ because of the low absorption probability of antineutrinos in the reactor. Also, the quantities $\overline{E}_{nd}$, $\overline{E}_{\gamma d}$ and $\overline{E}_{\beta}$ are time-dependent, and the full magnitude of the latter two quantities will not be realized for practicable irradiation and cooling times in a reactor. This again reduces the effective average total energy resulting directly from fission such that

$$Q_{eff} = Q_f' - \overline{E}_{\overline{\nu}} - \Delta\overline{E}_{\gamma d} - \Delta\overline{E}_{\beta}, \tag{8}$$

where the energies $\Delta\overline{E}_{\beta}$ and $\Delta\overline{E}_{\gamma d}$ depend on the irradiation history of the reactor. In addition to Q_{eff}, energy Q_c is liberated by the capture of the

remaining ($\bar{\nu}_T$ - 1) neutrons in the reactor materials. This latter energy is dependent on the neutron energy spectrum and the arrangement, amounts, and types of reactor materials.

The total energy Q_T released in fission and absorbed in a reactor is given finally by

$$Q_T = Q_{eff} + Q_c. \tag{9}$$

The present report critically reviews available information concerning the energy released by fission of the fissile nuclides ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu and the fertile nuclides ^{232}Th, ^{238}U, ^{240}Pu, and ^{242}Pu by neutrons having energies up to 14 MeV. Data are selected which, in our opinion, represent the most reliable values for each individual contribution to Q_f (Eq. 3). The values of Q_f' are calculated and compared for those fissioning systems where sufficient data exist by summation of the individual contributions (Eq. 3) and by the calculation involving energy-equivalent masses (Eq. 4). Values for the total energy release Q_T and the dependence of Q_T on the average energy of the captured neutron are calculated for a representative configuration of the Experimental Breeder Reactor II (EBR-II). Since Q_T depends on the specific details of the core and blanket configuration, these latter values must be considered as being illustrative only.

A summary of the energies of the individual contributions to Q_f and other pertinent reactor data has been compiled previously.[1] Early calculations using the energy-equivalent mass formalism (Eq. 4) were made by Walker.[2] Most recently, an excellent, thorough analysis of the energy release in the fission of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu by neutrons has been made by James.[3] In many aspects, for the sake of consistency and comparison, the present analysis closely parallels that of James.

This report has been prepared at the request of reactor physicists to provide a concise summary of the most reliable and accurate values for contributions to the total energy released in fission as well as accurate values for the total energy release. (Two companion reports[4,5] summarizing different aspects of the fission process have also been prepared.) Consequently, very little supplementary information on the details of various experimental methods used to obtain the data is given here. For further information, refer to the original references reported here or to several recent survey articles on nuclear fission.[6-9]

2. CALCULATION OF Q_f' FROM MASS EXCESSES

The quantity Q_f', the net average energy released directly from the fission process, has been calculated for a variety of fissioning systems for which complete mass-yield distributions are known using (1) Eqs. 6 and 7,

(2) the experimentally determined atomic masses tabulated by Mattauch et al.,[10] and (3) fission-fragment mass-yield distributions compiled by Meek and Rider,[11] Rider et al.,[12] and Harvey et al.[13] The calculated values of Q_f' depend on the length of time for which the energy release is integrated after fission. To compare the results for the energy release Q_f' calculated from nuclear masses to that obtained by summation of the individual contributions (see Sect. 4), the values of the average fragment mass excesses $\overline{X}_f = \sum_i Y_i m(A_i, Z_i)$ and consequently Q_f' were calculated for the stable end products of fission-product beta decay (infinite time after fission). Also, for illustration, the average fragment mass excesses have been calculated for integrating times of ~30 days, ~1 year, and ~100 years after fission by using the mass excesses for isobars with appropriate half-lives for each mass chain A_i. The results of these calculations for the average fragment mass excesses and Q_f' values are given in Table 1. The constancy of the average fragment mass excesses for different fissioning systems is clearly demonstrated by examination of the $\overline{X}_f(\infty)$ values given in Table 1. As mentioned before and illustrated in Fig. 1, this is attributable to the fact that the mass yields for the different fissioning systems considered here are similar and the mass excesses rather constant over the entire mass region of interest. As a result, the relative Q_f' values for different fissioning systems are mainly dependent on the relative masses of the targets and the average number of emitted neutrons. The constancy of the weighted fission-product mass excess (average value: -173.4 MeV for all systems) makes possible the estimation of the energy release from fission by using this mass calculation method for those fissioning systems for which no reliable mass-yield measurements exist. This procedure is illustrated in Table 1 by calculation of the Q_f' values for fission of ^{240}Pu and ^{242}Pu by fission-spectrum neutrons. Since no complete mass-yield measurements are available for these cases, the average fission-product mass excesses were taken to be equal to the average of the values for thermal-neutron

TABLE 1. Q_f' Calculated from Experimentally Determined Nuclear Masses

Target Nuclide	Neutron Energy	Y(A) Ref.	Mass Excess Target, MeV	$\overline{X}_f$, Average Mass Excess of Fission Products, MeV				$\overline{\nu}_T$ Measured[a]	Computed from Mass Yields		$(\overline{\nu}_T - 1)m_n$	$Q_f'(\infty)$
				30 days	1 yr	100 yr	Stable		$\overline{\nu}_T(\infty)$	$\overline{N}_\beta(\infty)$		
^{232}Th	FN[b]	13	35.512 ± 0.020	-170.90	-171.38	-171.80	-171.84 ± 0.20	2.36 ± 0.07	1.83	7.29	10.98 ± 0.56	196.37 ± 0.35
^{233}U	T[c]	12	36.814 ± 0.021	-172.35	-172.76	-173.12	-173.17	2.4866 ± 0.0069	2.46	5.15	12.00 ± 0.06	197.99 ± 0.21
^{235}U	T	11	40.906 ± 0.021	-172.51	-172.92	-173.27	-173.32	2.4229 ± 0.0066	2.49	6.14	11.48 ± 0.05	202.74 ± 0.21
^{235}U	FN	11	40.906 ± 0.021	-172.47	-172.88	-173.22	-173.28	2.52 ± 0.02	2.44	5.97	12.27 ± 0.16	201.92 ± 0.26
^{235}U	14[d]	11	40.906 ± 0.021	-173.45	-173.80	-174.10	-174.17	4.46 ± 0.10	4.22	5.21	27.93 ± 0.81	187.15 ± 0.83
^{238}U	FN	11	47.291 ± 0.021	-172.45	-172.86	-173.17	-173.21	2.81 + 0.05	2.84	6.73	14.61 ± 0.40	205.89 ± 0.45
^{238}U	14	11	47.291 ± 0.021	-172.93	-173.26	-173.54	-173.64	4.31 ± 0.08	4.80	6.57	26.72 ± 0.64	194.21 ± 0.67
^{239}Pu	T	11	48.573 ± 0.021	-173.03	-173.41	-173.71	-173.76	2.8799 ± 0.009	2.91	5.50	15.17 ± 0.07	207.16 ± 0.21
^{239}Pu	FN	11	48.573 ± 0.021	-172.80	-173.18	-173.48	-173.54	3.01 ± 0.05	2.57	5.15	16.22 ± 0.40	205.89 ± 0.45
^{241}Pu	T	11	52.849 ± 0.021	-172.95	-173.34	-173.64	-173.68	2.934 ± 0.012	2.86	6.25	15.61 ± 0.10	210.92 ± 0.22
^{240}Pu	FN	Est.	50.190 ± 0.020				-173.72[e]	3.17 ± 0.20[a]			17.5 ± 1.6	206.4 ± 1.6
^{242}Pu	FN	Est.	54.701 ± 0.023				-173.72[e]	3.18 ± 0.40[a]			17.6 ± 3.2	210.8 ± 3.2

[a]See Table 4.
[b]Fission-neutron spectrum.
[c]Thermal neutrons.
[d]14-MeV neutrons.
[e]Average of ^{239}Pu and ^{241}Pu $\overline{X}_f(\infty)$ values for thermal neutrons.

fission of ^{239}Pu and ^{241}Pu. Also to be noted from the time-dependent average fission-product mass excesses given in Table 1, an error less than 1 MeV will be made if the energy release values for infinity are used for integrating times greater than 30 days after fission has taken place. However, for short-term irradiations with integrating times less than 30 days, the time dependence must be analyzed in greater detail.

The average number of neutrons emitted, $\overline{\nu}_T(\infty)$, and the average total beta-decay chain lengths, $\overline{N}_{\beta T}(\infty)$, have also been calculated from the reported mass-yield distributions by using the following equations (the results are given in Table 1):

$$\overline{\nu}_T(\infty) = A_F - \sum_A AY(A) \tag{10}$$

and

$$\overline{N}_{\beta T}(\infty) = 2\left(\sum_A Z_S(A)Y(A)\right) - Z_F, \tag{11}$$

where A_F and Z_F are the mass and charge of the fissioning nucleus, $Y(A)$ the total cumulative yield for mass number A, and $Z_S(A)$ the "first" stable atomic number for the beta-decay mass chain A. The values of $\overline{\nu}_T(\infty)$ and $\overline{N}_{\beta T}(\infty)$ calculated in this manner serve as a check on the consistency of these parameters calculated by other methods later in this report.

3. INDIVIDUAL CONTRIBUTIONS TO TOTAL ENERGY RELEASE

3.1 Total Fragment Kinetic Energy Release, $\overline{E}_K$

Three basic methods have been used to measure the average total kinetic energy of the fragments, $\overline{E}_K$.

I. Calorimetric (C). In the calorimetric method, the heat generated when fragments are absorbed in a calorimeter is directly measured. Only a few such measurements have been reported using this method. The accuracy that can be achieved is uncertain, because of difficulties associated with determining the total number of fissions occurring during the heat measurements and the uncertainties in the corrections for heating of the calorimeter by beta particles and gamma rays.

II. Double Velocity (DV). In the DV method, the velocities of both fission fragments are measured simultaneously. Applying the laws of conservation of linear momentum and mass enables the preneutron emission masses, velocities, and kinetic energies of the fragments to be calculated. The DV measurements are difficult to perform because of low geometric efficiencies, but in principle can yield the most accurate absolute values.

III. Double Energy (DE). The DE method is the most widely used because of its simplicity and its high geometric efficiency. The kinetic energies of both fragments are measured simultaneously using two detectors (silicon solid-state detectors or gas-ionization chambers). The major difficulty with this method is the currently inadequate energy-calibration procedure. For solid-state and gas-ionization detectors, the pulse-height response for heavy ions (fission fragments) is not directly proportional to the energy, but is dependent on the mass and perhaps the nuclear charge of the fragments. Much of the existing $\overline{E}_K$ data reported in the literature using this method is based on energy calibrations obtained simply by normalizing measured ^{235}U or ^{252}Cf pulse-height spectra to the energy spectra obtained from various double velocity experiments. Hence, (1) these double-energy results are not truly independent measurements, but are calibrated relative to different $\overline{E}_K$ standards, and (2) the results obtained for fissioning systems different from the calibration standard are questionable, because of the omission of the mass dependence from the calibration. For the more recently obtained data using gold-surface barrier detectors, a more precise energy-calibration method has been used which includes an approximate mass dependency.[14] This calibration is based on the pulse-height response of the detectors to monoenergetic bromine and iodine ions.

The criteria used in this work for the selection of the most accurate literature values of $\overline{E}_K$ and the comparison of the results obtained using these three methods are:

1) The E_K measurement using one of the three basic methods should be independent of the other methods. Consequently, for the double-energy method, only those values obtained using the mass-dependent energy calibration[14] have been used.

2) The sum of both fragment energies must have been determined for each observed event.

3) All necessary corrections, such as those for neutron emission and energy loss in the target material, must have been applied to the double-velocity and -energy data.

The published results of double-velocity and -energy measurements have generally been corrected for neutron emission and represent the initial total kinetic energy before neutron emission has taken place, $\overline{E}_{Ki}$. The heat produced by stopping fragments (as measured calorimetrically and of importance in reactor work) results from the final total kinetic energy after neutron emission from the fragments, $\overline{E}_{Kf}$. The relationship between the average initial and final total kinetic energies is given by

$$\overline{E}_{Kf} = \frac{\overline{E}_{Ki}}{C} \tag{12}$$

and

$$C = 1 + \frac{\bar{\nu}_T}{2A_F}\left(\frac{\bar{A}_L}{\bar{A}_H} + \frac{\bar{A}_H}{\bar{A}_L}\right), \tag{13}$$

where $\bar{A}_L$ and $\bar{A}_H$ are the average preneutron emission masses of the light and heavy fragments, respectively.

The $\bar{E}_K$ results that satisfy the previously stated criteria are given in Table 2 with various averaged values. Total kinetic-energy values are also given for the spontaneous fission of ^{252}Cf, which is a commonly used $\bar{E}_K$ standard. Comparison of the individual and weighted average results of the double-velocity and -energy methods discloses a discrepancy of about 4 MeV between the results of the two methods, several times greater than the quoted standard deviations. This discrepancy, which is nearly constant over a wide range of fissioning nuclides, is more clearly illustrated in Fig. 2, where the initial $\bar{E}_{Ki}$ values are plotted as a function of the parameter $Z_F^2/A_F^{1/3}$. Here Z_F and A_F are the nuclear charge and mass number of the fissioning nucleus, respectively. A simple model predicts that the E_{Ki} values have a linear dependency on the $Z_F^2/A_F^{1/3}$ parameter.[15]

TABLE 2. Summary of $\bar{E}_K$ Data

^{232}Th	^{233}U	^{235}U	^{238}U	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{252}Cf	Method[a]	Ref.
	167.02 ± 0.17	167.68 ± 1.7		174.41 ± 1.7					DV, i	17
		167.45 ± 1.7							DV, i	18
								185.7 ± 1.9	DV, i	19
								182.1 ± 1.7	DV, i	20
				177.7 ± 1.8		179.6 ± 1.8			DE, i	21
		171.9 ± 1.4						186.5 ± 1.2	DE, i	22
	171.2 ± 2.0	172.0 ± 2.0	170.1 ± 2.0	179.3 ± 2.0				184.3 ± 2.0	DE, i	16
	172.1 ± 1.8	172.0 ± 1.8		177.1 ± 1.8				185.8 ± 1.8	DE, i	23
	172.0 ± 1.8								DE, i	24
163.02 ± 2.0[b]									DE, i	25
169.7 ± 2.0[c]									DE, i	26
	167.02 ± 1.7	167.57 ± 1.2		174.41 ± 1.7				183.70 ± 1.3	DV, i weighted average	
d	171.80 ± 1.1	171.95 ± 1.0	170.1 ± 2.0	177.95 ± 1.1		179.6 ± 1.8		185.89 ± 0.98	DE, i weighted average	
161.79[e]	169.41	169.76	167.93[f]	176.18	176.24[e]	177.81[g]	175.69[e]	184.80	DE-DV, i arithmetic average	
160.02[f]	167.49	167.91	165.89	173.97	173.83[e]	175.57[g]	173.99[e]		DE-DV, f arithmetic average	
		167.1 ± 1.6							C, f	27
		166 ± 2							C, f	28

[a]DV = double-velocity method; DE = double-energy method; C = calorimetric method; i = initial preneutron emission $\bar{E}_K$; and f = final postneutron emission $\bar{E}_K$.

[b]$\bar{E}_{Ki}$ value obtained for $\bar{E}_n$ = 2.87, which is near the average captured-neutron energy for an incident fast-neutron spectrum. We assigned an error of ±0.22 MeV, which must indicate relative precision and not the absolute error. We have assigned the typical absolute error of ±2.0 MeV to this value.

[c]Value obtained for E_n = 2.97 MeV.

[d]No average value was calculated, because of the large discrepancy between the two reported values.

[e]Calculated using Eq. 16.

[f]DE value normalized to a hypothetical arithmetic mean of DV and DE measurements using the factor of 0.987264 obtained from the ratio of the arithmetic mean to DE value for ^{235}U.

[g]Same as (d), using factor of 0.99005 obtained from ^{239}Pu data.

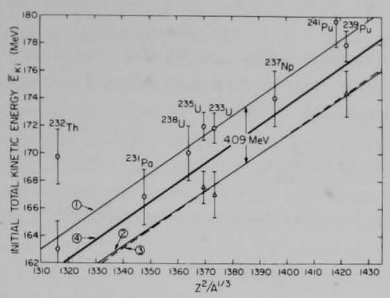

Fig. 2

Dependence of Preneutron-emission (initial) Total Kinetic Energies on the Parameter $Z_F^2/A_F^{1/3}$: (1) Least-squares Fit to Double-energy (DE) Data $\bar{E}_{Ki} = 0.139601Z_F^2/A_F^{1/3} - 19.935$; (2) Least-squares Fit to Double-velocity (DV) Data $\bar{E}_{Ki} = 0.136514Z_F^2/A_F^{1/3} - 19.747$; (3) Results of (1) Decreased by 4.09 MeV; (4) Representative Average of DV and DE Data; Results of (1) Reduced by 2.04 MeV: $\bar{E}_{Ki} = 0.139601Z_F^2/A_F^{1/3} - 21.975$. ANL Neg. No. 121-7163 Rev. 1.

In addition to the double-energy data given in Table 2, $\bar{E}_{Ki}$ values for fission-spectrum neutron-induced fission of ^{231}Pa and ^{237}Np (Ref. 16) have been included. The results of weighted linear least-squares fits to the double-velocity and -energy data are

$$\bar{E}_{Ki}(DE) = 0.139601Z_F^2/A_F^{1/3} - 19.935 \tag{14}$$

and

$$\bar{E}_{Ki}(DV) = 0.13651Z_F^2/A_F^{1/3} - 19.747. \tag{15}$$

The ^{232}Th data were not included in the least-squares fit, because of the large discrepancy between the two reported values. From Fig. 2, the linear dependency of $\bar{E}_{Ki}$ with $Z_F^2/A_F^{1/3}$ is seen to be a good assumption, and the data from the double-velocity and -energy methods appear to be similar, except for a 4.1-MeV displacement. The dashed line in Fig. 2 represents the least-squares fit for the double-energy values reduced by 4.1 MeV. There is currently no quantitative explanation for this discrepancy between the two experimental methods. However, the double-velocity $\bar{E}_{Ki}$ data of Milton and Fraser[17] are generally considered to be low as the result of small-angle scattering of the fragments in the flight tubes. On the other hand, the double-energy $\bar{E}_{Ki}$ data may be high because of the omission of a nuclear-charge dependency in the energy calibration. Wilkins[29] has estimated that the measured value of $\bar{E}_{Ki}$ for ^{252}Cf spontaneous fission decreases by ~1.5 MeV with the inclusion of the nuclear-charge dependency. In light of these possible trends in the systematic errors of the two methods (the DV values possibly low, and DE values possibly high), we have assumed that the more correct $\bar{E}_{Ki}$ values are represented by the arithmetic mean of the DV and DE results. The arithmetic mean value of $\bar{E}_{Kf}$ for ^{235}U is seen from Table 2 to be in good agreement with the calorimetric values. For ^{232}Th and those systems in which $\bar{E}_K$ values have not been determined (^{240}Pu and ^{242}Pu), we have used values calculated from the results of the linear least-squares fit to the double-energy data decreased by a constant 2.04 MeV as representative of the arithmetic average of double-velocity and -energy results:

$$E_{Ki}(avg) = 0.139601 Z_F^2/A_F^{1/3} - 21.975. \quad (16)$$

The $\bar{E}_K$ values obtained using the arithmetic average of the results obtained by both methods and also calculated from Eq. 16 are assumed throughout this work to all have the same uncertainty of ±2 MeV.

3.2 Average Energy Released by Neutrons, $\bar{E}_n$

The average kinetic energy per fission released by neutrons is

$$\bar{E}_n = \bar{\nu}_p B_p + \bar{\nu}_d B_d, \quad (17)$$

where $\bar{\nu}$ is the average number of prompt p or delayed d neutrons emitted per fission, and B is the average energy per neutron.

Table 3 lists measured values of $\bar{\nu}_d$ for various fissioning systems. The bombarding-neutron spectrum used for the indicated "fission-neutron" measurements was that of the GODIVA bare ^{235}U metal assembly.

TABLE 3. Delayed-neutron Yields for Various Incident Neutron Energies

	E_i			
Nuclide	Thermal[a]	Fission Neutrons[a,b]	3.1 MeV[c]	14.9 MeV[c]
^{232}Th	0.0066 ± 0.0003	0.0496 ± 0.0020	0.060 ± 0.006	0.031 ± 0.0004
^{233}U	0.0066 ± 0.0003	0.0070 ± 0.0004	0.0077 ± 0.0008	0.0043 ± 0.0004
^{235}U	0.0158 ± 0.0005	0.0165 ± 0.0005	0.018 ± 0.002	0.0095 ± 0.0008
^{238}U		0.0412 ± 0.0017	0.049 ± 0.005	0.028 ± 0.0025
^{239}Pu	0.0061 ± 0.0003	0.0063 ± 0.0003	0.0069 ± 0.0007	0.0043 ± 0.0004
^{240}Pu		0.0088 ± 0.0006		0.0057 ± 0.0007
^{241}Pu				0.0084 ± 0.0012

[a]Data from Ref. 33.
[b]Neutrons from the GODIVA assembly.
[c]Data from Ref. 34.

Little information is available on the energy spectra of the delayed neutrons. Three measurements[30-32] for the fission of ^{235}U give an average neutron energy of 0.52 or 0.56 MeV per neutron, depending on whether all six half-life groups are considered in the averaging or only those groups for which energy measurements are reported. Fortunately, because of the small number of delayed neutrons emitted per fission, $\bar{E}_{nd}$ is small relative to $\bar{E}_{np}$. A value of B_d equal to 0.54 ± 0.10 was used for all nuclides. Calculated values of $\bar{E}_{nd}$ are given in column eight of Table 4.

Extensive measurements have been made of $\bar{\nu}_p$ at thermal-neutron energies and as a function of incident neutron energy. Column three of Table 4 lists $\bar{\nu}_T$, the total number of neutrons, $\bar{\nu}_p + \bar{\nu}_d$, emitted per fission

for thermal-neutron energies and fission neutrons. The thermal-neutron values are those recently revised by the IAEA committee.[35] The values of $\bar{\nu}_T$ for fission neutrons have been calculated for an incident neutron spectrum of the form shown in Fig. 3 using the group fission cross sections reported by Davey[36] and the energy dependence of $\bar{\nu}_T$ recommended by Fillmore.[37] The above neutron spectrum represents a hypothetical neutron spectrum for the center of a Zero Power Reactor (ZPR) assembly and corresponds approximately to the homogenized core composition of an EBR-II loading.[38] There is a slight discrepancy of 0.2% between the value of $\bar{\nu}_p$ (3.764) for ^{252}Cf used by Fillmore[37] to normalize his data and the value given in Table 4. This results in calculated $\bar{\nu}_T$ values that may be as much as 0.01 neutron per fission too large.

TABLE 4. Average Neutron Energy per Fission

Nuclide	E_i	$\bar{\nu}_T$	$\bar{\nu}_p$	B_p (experimental) (calculated)	B_p[a]	$\bar{E}_{np}$	$\bar{E}_{nd}$	$\bar{E}_n$
1. ^{233}U	Thermal	2.4866 ± 0.0069[b]	2.480	1.973 ± 0.062[c]	1.963 ± 0.042	4.893 ± 0.154[d]	0.004 ± 0.001	4.897 ± 0.154
2. ^{235}U	Thermal	2.4229 ± 0.0066[b]	2.407	1.943 ± 0.044[c]	1.950 ± 0.042	4.677 ± 0.107[d]	0.009 ± 0.002	4.686 ± 0.107
3. ^{239}Pu	Thermal	2.8799 ± 0.0090[b]	2.874	2.041 ± 0.038[c]	2.029 ± 0.044	5.866 ± 0.111[d]	0.003 ± 0.001	5.869 ± 0.111
4. ^{241}Pu	Thermal	2.934 ± 0.0012[b]	2.919	2.002 ± 0.051[e]	2.037 ± 0.044	5.844 ± 0.149[d]	0.008 ± 0.002[f]	5.852 ± 0.149
5. ^{232}Th	Fission neutrons[g]	2.36 ± 0.07[h]	2.31		1.933 ± 0.043	4.46 ± 0.17[i]	0.027 ± 0.005	4.49 ± 0.17
6. ^{233}U	Fission neutrons[g]	2.55 ± 0.04[h]	2.54		1.973 ± 0.043	5.01 ± 0.14[i]	0.004 ± 0.001	5.02 ± 0.14
7. ^{235}U	Fission neutrons[g]	2.52 ± 0.02[h]	2.50		1.966 ± 0.043	4.92 ± 0.11[i]	0.009 ± 0.002	4.92 ± 0.11
8. ^{238}U	Fission neutrons[g]	2.81 ± 0.05[h]	2.77		2.012 ± 0.044	5.57 ± 0.16[i]	0.022 ± 0.004	5.60 ± 0.16
9. ^{239}Pu	Fission neutrons[g]	3.01 ± 0.05[h]	3.00		2.052 ± 0.046	6.15 ± 0.17[i]	0.003 ± 0.001	6.15 ± 0.17
10. ^{240}Pu	Fission neutrons[g]	3.17 ± 0.20[h]	3.16		2.076 ± 0.055	6.56 ± 0.45[i]	0.005 ± 0.001	6.56 ± 0.045
11. ^{241}Pu	Fission neutrons[g]	3.06 ± 0.12[h]	3.04[f]		2.056 ± 0.049	6.25 ± 0.29[i]	0.008 ± 0.002	6.26 ± 0.29
12. ^{242}Pu	Fission neutrons[g]	3.18 ± 0.40[h,j]	3.16[k]		2.076 ± 0.078	6.56 ± 0.87[i]	0.012 ± 0.003	6.57 ± 0.87
13. ^{252}Cf	Spontaneous fission	3.765 ± 0.012[b]	3.756	2.216 ± 0.158[c]	2.168 ± 0.048	8.141 ± 0.182[d]	0.005 ± 0.001	8.146 ± 0.182

[a]Calculated from the relationship $B_p = 0.75 + 0.65\sqrt{\bar{\nu}_p + 1}$ (Ref. 39).
[b]Data from Ref. 35.
[c]Arithmetic average of several measurements.[4]
[d]Calculated using B_p (experimental).
[e]Data from Ref. 40.
[f]$\bar{\nu}_d = 0.015$ (Ref. 37).
[g]Fission-neutron spectrum of the form shown in Fig. 3.
[h]Calculated for fission-neutron spectrum given by (f), group fission cross sections given in Ref. 36, and $\bar{\nu}_T$ as a function of E_i given in Ref. 37. The errors are representative of those of $\bar{\nu}_T$ (E_i) measurements and do not reflect errors in the fission cross sections or neutron flux.
[i]Calculated using B_p (calculated).
[j]$\bar{\nu}_T(E)$ assumed to be the same for ^{242}Pu as for ^{240}Pu.
[k]$\bar{\nu}_d$ estimated to be 0.023 ± 0.003.

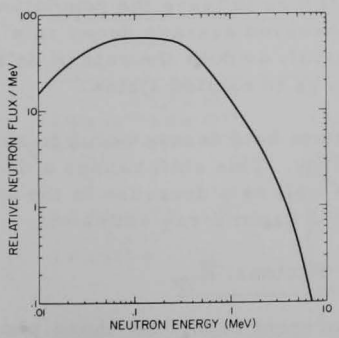

Fig. 3

Hypothetical Neutron-energy Spectrum for the Center of a ZPR Assembly Which Approximates That of a Homogenized Core Composition of an EBR-II Loading (Ref. 38). ANL Neg. No. 121-7162.

Jaffey[4] has recently surveyed measurements of the energy spectra of fission neutrons. Although there is considerable disagreement between the average neutron energy B_p measured by various investigators, calculations of $\overline{E}_{np}$ using the extreme measurements of B_p indicate a variation of only 0.6-0.7 MeV per fission. Values of B_p (experimental) listed in Table 4 represent an arithmetic average of recent measurements.[4] Values of B_p (calculated) were calculated from the relationship

$$B_p = 0.75 + 0.65 \sqrt{\overline{\nu}_p + 1}, \tag{18}$$

given by Terrell.[39]

3.3 Average Energy Released as Photons, $\overline{E}_\gamma$

3.3.1 Introduction

The rate of emission of gamma rays following fission has been described theoretically by Griffin.[41] An adaptation of this description is presented as an introduction to this section.

Shortly after the emission of neutrons by the highly excited fission fragments, the remaining excitation is removed by the rapid emission of gamma rays. Gamma rays are emitted until the fragment reaches its ground state or an excited isomeric state whose decay is much slower than the typical gamma decays. Most of this gamma radiation is emitted within 10^{-6} sec after fission. However, gamma rays continue to be emitted at a decreasing rate for times up to 10^{-3} sec after fission.

For times between 10^{-3} and 10^{-1} sec, a plateau is observed in the gamma-ray intensity. Since the typical fission fragment has reached its ground state by 10^{-3} sec, its next decay will be a beta decay. This generally requires a time on the order of seconds. During this period, a few beta decays will occur, followed by gamma-ray emission whenever the beta decay goes to an excited state of the daughter nucleus. For times short compared to 10^{-1} sec, these decays are so few as to leave the populations of the various fragments unchanged. The observed average decay rate therefore remains constant during this interval, as does the rate of delayed gamma-ray emission arising from beta decays to excited states.

For times greater than 1 sec, sufficient beta decays occur to shift the fragment population closer toward stability. This shift causes a decrease in the average beta-decay energy as well as a decrease in the average rate of beta decay and subsequent delayed gamma-ray emission.

3.3.2 Average Energy Released by Prompt Photons, $\overline{E}_{\gamma p}$

Prompt photons are defined in the present report as those photons associated with the deexcitation of the fission fragments before beta decay. They are assumed to occur within 1 msec after fission.

The most extensive measurements have been made on the fission of ^{235}U. These measurements cover nearly the entire range from 0 to 10^{-3} sec after fission, if one assumes there is little difference in the gamma-ray emission associated with the fission of ^{235}U by thermal or fission spectrum neutrons. (Protopopov and Shiriaev[42] have reported that the average total energy of gamma rays emitted within 2×10^{-7} sec after fission of ^{235}U by thermal, 2.8-, and 14.7-MeV neutrons is the same within an experimental accuracy of ±15%.)

Peelle and Maienschein[43] have recently completed an analysis of data on the gamma rays emitted within 6.9×10^{-8} sec after fission of ^{235}U by thermal neutrons. They determined that within this time an average energy of 7.25 ± 0.26 MeV was released per fission by an average of 8.13 ± 0.35 photons with energies from 10 keV to 10.5 MeV. A negligible energy yield is expected by gamma rays less than 10 keV or greater than 10.5 MeV. Less than 0.1 photon per fission is expected below 10 keV, and none is expected above 10.5 MeV.

The value of 7.25 ± 0.26 MeV per fission is used in the present report (see Table 5) as the energy released within the first 69 nsec after the fission of ^{235}U. This is somewhat greater than the energy release measured by Verbinski et al.[44] within the first 10 nsec. They found 6.51 ± 0.3 MeV were emitted by 6.69 ± 0.3 photons within the shorter time range. Gamma rays with energies between 140 keV and 10 MeV were measured. They estimated that 0.1 MeV per fission might be released by photons of lower energy. A time-of-flight technique was employed to exclude neutron backgrounds. Figure 4 compares the gamma-ray spectra of Verbinski et al.[44] and Peelle and Maienschein.[43] The results of Verbinski et al. are typically about 10% lower than those of Peelle and Maienschein. Causes for the disagreement between the two spectra may be attributable to exclusion of some gamma rays because of the shorter coincidence resolving time in the Verbinski et al. experiment, neutron effects in the Peelle and Maienschein

TABLE 5. Average Energy Released by Photons at Various Times after the Fission of ^{235}U by Neutrons

Time, sec	$\bar{E}_\gamma$, MeV fission^{-1}	Remarks and References
$0\text{-}6.9 \times 10^{-8}$	7.25 ± 0.26	Ref. 43.
$6.9 \times 10^{-8}\text{-}1.0 \times 10^{-6}$	0.353 ± 0.706	See text. Refs. 45-47.
$1.0 \times 10^{-6}\text{-}1.0 \times 10^{-3}$	0.037 ± 0.021	See text. Refs. 47-49.
	$\bar{E}_{\gamma p}$ = 7.64 ± 0.75	
$1.0 \times 10^{-3}\text{-}1.0$	0.52 ± 0.26	See text.
$1.0\text{-}1.0 \times 10^{8}$	6.65 ± 1.3	Refs. 50, 51.
$1.0 \times 10^{8}\text{-}\infty$	0.032	Ref. 3.
	$\bar{E}_{\gamma d}$ = 7.20 ± 1.3	
	$\bar{E}_\gamma$ = 14.84 ± 1.5	

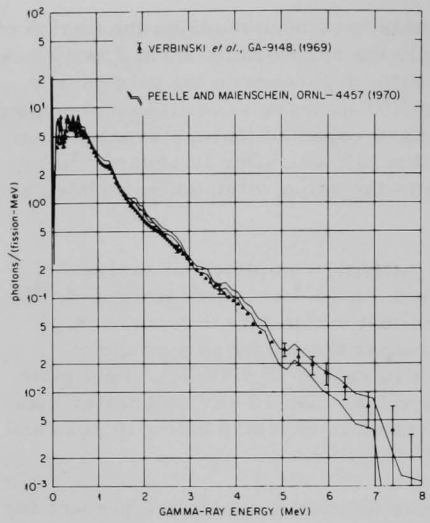

Fig. 4. Gamma-ray Spectra Measured within the First 69 nsec (Ref. 43) and 10 nsec (Ref. 44) after the Fission of ^{235}U by Thermal Neutrons. ANL Neg. No. 121-6962.

work, in which a NaI detector was employed, or in the determination of the detector-response function to gamma rays of various energies and the subsequent unfolding problems more or less common to the two measurements.

In an early paper, Maienschein et al.[45] reported that from 5×10^{-8} to 10^{-6} sec after fission $(5.7 \pm 0.3)\%$ as many counts were observed over the energy range from 0.15 to 1.93 MeV as were observed in the first 5×10^{-8} sec for the same energy range. Assuming the gamma-ray energy spectrum in the longer time region to be the same as that for the very prompt gamma rays ($\leq 6.9 \times 10^{-9}$ sec), the energy released in the longer time region is $0.057 \times 7.25 = 0.413$ MeV per fission. Maienschein[46] later presented the average energy released as a function of time from 5×10^{-8} to 10^{-6} sec. These data, as interpreted from his Fig. 4.6.1, are presented in Fig. 5. Conservative limits of a factor-of-two have been placed on these data.[46] Figure 5 also shows an

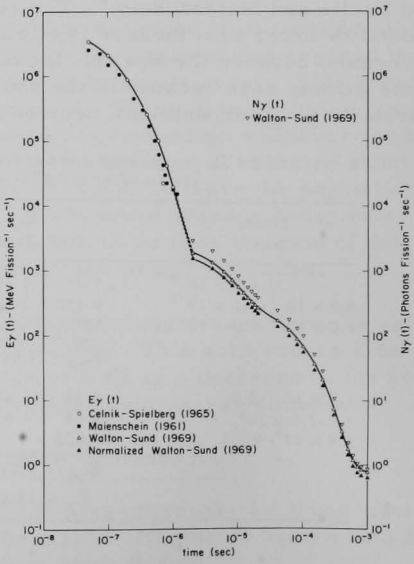

Fig. 5

Energy Released by Photons and Number of Photons Emitted per Fission of ^{235}U by Thermal- or Fission-spectrum Neutrons as a Function of Time ≤ 1 msec after Fission. ANL Neg. No. 121-7129.

interpretation of the Maienschein et al.[45] data made by Celnik and Spielberg[47] normalized to give an energy release of 0.413 MeV per fission, as calculated above. These latter data, plotted on a semilogarithmic scale, form nearly a straight line from 5×10^{-8} to 10^{-7} sec. Therefore a relationship of the form $E(t) = ae^{bt}$ has been fitted to the data and integrated from 5×10^{-8} to 6.9×10^{-8} sec, yielding a value of 0.060 MeV per fission. Subtracting this from the 0.413 MeV per fission determined previously gives 0.353 MeV per fission released from 6.9×10^{-8} to 10^{-6} sec. A factor-of-two uncertainty is assigned to this energy release (see Table 5).

Walton and Sund[48,49] have determined the energy released and the intensity of photons with energies >140 keV as a function of time from 2×10^{-6} to 2.5×10^{-2} sec after fission of ^{235}U by fission spectrum neutrons. These data are presented in Fig. 5 by the open triangles. Triangles pointed upward represent energy-emission rates $E_\gamma(t)$. Triangles pointed downward represent photon-intensity rates $N_\gamma(t)$. Walton and Sund[49] have estimated an uncertainty of ~30% in the intensities of photons with energies >510 keV in the plateau region up to 0.025 sec (see Fig. 6). Allowing for photons of lower energies, an uncertainty of 50% in the energy-emission rates appears to be a fairly realistic estimate. The energy-emission rates have been fitted over various time ranges from 2×10^{-6} to 10^{-3} sec by analytical expressions of the form $E(t) = ae^{bt} + ce^{dt}$. These expressions have been integrated and summed to give an average energy release of 0.030 ± 0.015 MeV per fission. Interpolation of the normalized data of Celnik and Spielberg[47] at 10^{-6} sec to that of Walton and Sund[49] at 2×10^{-6} sec, as shown in Fig. 5, gives an additional energy release of 0.007 ± 0.014 MeV per fission. The average total energy released by photons from 10^{-6} to 10^{-3} sec after fission is then 0.037 ± 0.021 MeV per fission (see Table 5).

Summation over the various time regions from 0 to 10^{-3} sec after fission, as in Table 5, gives an energy release by prompt photons of 7.64 ± 0.75 MeV per fission. This is somewhat lower than the value of 8.01 ± 0.87 MeV used by James[3] based on the analysis by Holden et al.[52] However, both values agree well within the quoted uncertainties.

Recent measurements by Berick et al.[53] of the intensities of gamma rays with energies >380 keV from 0.01 to 4 sec after fission of ^{235}U indicate that the Walton and Sund[48,49] data may have been normalized to too large a value in the plateau region (see Fig. 6). We have therefore converted the intensity rates determined by Berick et al.[53] into energy-emission rates.

The intensity rates determined by Berick et al.[53] for photons with energies >380 keV were normalized to the rates determined by Fisher and Engle[54] to include a broader spectrum of photon energies. An average (1.515) of the normalization constants determined at 0.35 and 1.5 sec after fission was applied to the data of Berick et al.[53] To convert to energy-emission rates, an average energy (0.940 MeV) per photon determined from

the measurements of Fisher and Engle[54] at 0.35 and 1.5 sec was applied to the normalized photon-intensity rates. The energy-emission rates so derived are given in Fig. 6 and are referred to as the "normalized" Berick et al. data. The energy-emission rates of Walton and Sund[48,49] were then normalized to the normalized data of Berick et al.[53] at 0.025 sec after fission. The "normalized" Walton and Sund data are given as solid triangles in Figs. 5 and 6. Interpolation to the normalized Walton and Sund data, as shown in Fig. 5, and integration of the data to 1 msec after fission gives 0.031 MeV per fission. The difference between this value and that derived directly from the data of Walton and Sund is almost negligible.

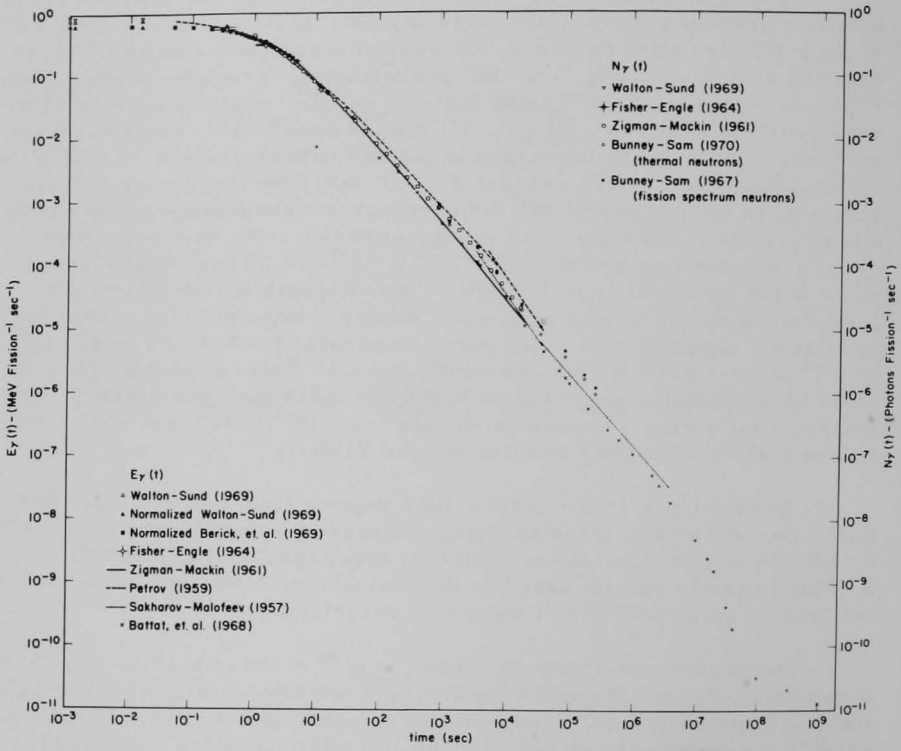

Fig. 6. Energy Released by Photons and Number of Photons Emitted per Fission of ^{235}U by Thermal- or Fission-spectrum Neutrons as a Function of Time ≥1 msec after Fission. ANL Neg. No. 121-7130.

Sufficient measurements have been made of the prompt gamma rays following the fission of ^{239}Pu by neutrons to approximate the average energy released by them. Verbinski et al.[44] have measured the average energy released within 10^{-8} sec by gamma rays with energies >140 keV to be 6.82 ± 0.3 MeV per fission. If one assumes that the energy spectrum is the same

within 10^{-6} sec as it is within 10^{-8} sec, then by using the Verbinski et al.[44] measurements with ^{239}Pu and ^{235}U to normalize to the 7.60 ± 0.75 MeV released per ^{235}U fission within the first μsec, we obtain a value of 7.96 ± 0.94 MeV per ^{239}Pu fission. Interpolation to 2 μsec and integration of the data of Walton and Sund[48,49] for ^{239}Pu to 1 msec gives an energy release of 0.054 ± 0.029 MeV per fission. Interpolation and integration of the normalized Walton and Sund data give 0.049 ± 0.027 MeV per fission. The average energy released by prompt gamma rays in the fission of ^{239}Pu by thermal or fission spectrum neutrons is therefore taken to be 8.01 ± 0.94 MeV per fission (see Table 6). Note that if the energy release were calculated by using the Verbinski et al.[44] measurements on ^{239}Pu and ^{235}U to normalize to the 7.64 ± 0.75 MeV per fission obtained for ^{235}U over the first msec, a value of 8.00 ± 0.94 MeV per fission would be obtained.

TABLE 6. Average Energy Released by Photons at Various Times after the Fission of ^{239}Pu by Neutrons

Time, sec	$\bar{E}_\gamma$, MeV fission^{-1}	Remarks and References
$0\text{-}1.0 \times 10^{-6}$	7.96 ± 0.94	Calculated using ^{235}U data. See text. Refs. 43-47.
$1.0 \times 10^{-6}\text{-}1.0 \times 10^{-3}$	0.05 ± 0.03	Refs. 47-49, 53, 54.
	$\bar{\bar{E}}_{\gamma p}$ = 8.01 ± 0.94	
$1.0 \times 10^{-1}\text{-}2.0 \times 10^{-1}$	0.10 ± 0.05	Normalized data of Refs. 48, 49, 53.
$2.0 \times 10^{-1}\text{-}4.5 \times 10$	2.86 ± 0.71	Ref. 54.
$4.5 \times 10\text{-}2.0 \times 10^{2}$	0.99 ± 0.25	Ref. 50.
$2.0 \times 10^{2}\text{-}1.0 \times 10^{8}$	2.46 ± 0.62	Ref. 55.
$1.0 \times 10^{8}\text{-}\infty$	0.03	Ref. 3.
	$\bar{\bar{E}}_{\gamma d}$ = 6.44 ± 0.98	
	$\bar{E}_\gamma$ = 14.45 ± 1.4	

Little information concerning prompt gamma-ray emission is available for other fissioning systems. Early measurements of the average energy released in the spontaneous fission of ^{252}Cf by prompt gamma rays were 9 MeV per fission[56] without a time interval specified and 8.2 MeV per fission[57] within ~3×10^{-9} sec. Verbinski et al.[44] have also measured gamma rays with energies >140 keV emitted within 10^{-8} sec after fission for this system. They found the average energy released to be 6.84 ± 0.3 MeV per fission. Using the ^{235}U data as described above to obtain the energy released within the first msec, a value of 8.03 ± 0.94 MeV per fission is obtained. The energy spectra derived by Verbinski et al.[44] for the thermal-neutron fission of ^{235}U and ^{239}Pu and the spontaneous fission of ^{252}Cf are very similar. The spectrum of ^{252}Cf exhibits about 50% more gamma rays below 0.7 MeV than that of ^{235}U and fewer gamma rays above

5.0 MeV. The spectrum of ^{239}Pu is very much like that of ^{235}U, having somewhat more gamma rays below 0.7 MeV than the latter. Protopopov and Shiriaev[42,58] have reported that, within their experimental accuracy (±15%), the average total energies of gamma rays emitted in the fission of ^{238}U and ^{235}U by 2.8- and 14.7-MeV neutrons are the same as for ^{235}U by thermal neutrons. In view of these latter results, the fission gamma-ray spectra of ^{235}U, ^{239}Pu, and ^{252}Cf, and the values of $\bar{E}_{\gamma p}$ derived for the same nuclides, it appears that a value of approximately 8 MeV per fission is appropriate for $\bar{E}_{\gamma p}$ for all nuclides under consideration. We therefore assign a value of 7.6 ± 1.5 MeV per fission to all those nuclides other than ^{235}U and ^{239}Pu (see Table 7). The change in this value with incident neutron energy appears to be very small.

TABLE 7. Average Energy Released as Photons within 1 msec after Fission by Neutrons

Nuclide	$\bar{E}_{\gamma p}$, MeV fission^{-1}
^{235}U	7.64 ± 0.75
^{239}Pu	8.01 ± 0.94
^{232}Th, ^{233}U, ^{238}U, ^{240}Pu, ^{241}Pu, ^{242}Pu	7.6 ± 1.5

3.3.3 Average Energy Released by Delayed Photons, $\bar{E}_{\gamma d}$

Delayed gamma rays are defined in the present report as those gamma rays associated with the beta decay of fission products. They occur at times $>10^{-3}$ sec after fission.

As with prompt gamma rays, most investigations of delayed gamma rays have been made in the fission of ^{235}U by thermal or fission spectrum neutrons. There are several experimental measurements of photon intensity or energy-emission rates that investigate the time range from 10^{-3} to 1 sec. The results of some of these investigations are shown in Fig. 6. Integration of the various data from 10^{-3} to 1 sec gives nearly identical values of the energy release. Integration of the Walton and Sund[48,49] data from 0.001 to 0.025 sec, interpolation to the Petrov data[59] at 0.05 sec, and integration of the latter data yield an energy release of 0.52 ± 0.26 MeV per

fission. Integration of the normalized Walton and Sund data[48,49] from 0.001 sec to either 0.01 or 0.025 sec and of the normalized Berick et al.[53] data from either 0.01 or 0.025 sec to 1 sec gives 0.50 ± 0.025 MeV per fission. The 0.52 ± 0.26 MeV value is given in Table 5. Iyer and Ganguly[60] have indicated a gamma-ray energy release from 0.01 to 1 sec after fission of 0.442 MeV per fission. Integration of the data of Walton and Sund[48,49] and Petrov[59] over this time range gives 0.514 MeV per fission. Integration of the normalized data of Walton and Sund and Berick et al. gives 0.494 MeV per fission. The agreement between these three values is rather good for this time range.

Holden et al.[52] have reported an energy release of 6.65 MeV per fission by gamma rays emitted from 1 to 10^8 sec after fission. This value has been used by James[3] with an uncertainty of 1.3 MeV per fission suggested by Story.[61] Much of the experimental data for gamma rays emitted in this time range is shown in Fig. 6. The data of Zigman and Mackin[50] are based on measurements made at the U.S. Naval Radiological Defense Laboratory and the Knabe and Putnam[62] summary of experimental work done at Oak Ridge National Laboratory. The crosses in Fig. 6 represent the calculated results of Battat et al.[55] As can be seen from Fig. 6, there is close agreement between the results of Fisher and Engle,[54] Petrov,[59] and Zigman and Mackin[50] for the first 45-60 sec after fission. Integration of the Petrov curves from 1 to 60 sec gives an energy release of 2.98 MeV per fission; integration of the Zigman and Mackin curve over the same time range gives 2.87 MeV per fission. At longer times, there is a larger discrepancy between the two sets of data. Integration of the Petrov curves from 60 to 18,000 sec gives 4.56 MeV per fission. Integration of the Zigman and Mackin curve over the same time range gives 2.66 MeV per fission. The data of Sakharov and Malofeev[51] are consistently lower than those of Petrov.[59] Data of the former, however, appear to extend the data of Zigman and Mackin[50] for times >18,000 sec. The calculated results of Battat et al.[55] agree well with the Zigman and Mackin data for times >200 sec after fission. In the interval 200 to 18,000 sec after fission, integration of the Zigman and Mackin curve gives an energy release of 1.88 MeV per fission. The results of Battat et al. are slightly lower than the results of Sakharov and Malofeev.[51] The integrated energy release from 1.8×10^4 to 3.6×10^6 sec after fission obtained from the Battat et al. data is 0.706 MeV per fission; from the Sakharov and Malofeev data, 0.931 MeV per fission. The Battat et al. data indicate a perceptible decrease in the energy emitted by gamma rays $>3.6 \times 10^7$ sec after fission (see Fig. 6). This is consistent with other calculated results such as Perkins and King,[63] Perkins,[64] Knabe and Putnam,[62] and Brunner and Edwards.[65] Integration of the data of Battat et al.[59] from 3.6×10^7 to 10^8 sec after fission gives an energy release of 0.115 MeV per fission. Summing the energies released obtained from the data of Zigman and Mackin[50] from 1 sec to 1.8×10^4 sec, the data of Sakharov and Malofeev[51] from 1.8×10^4 to 3.6×10^6 sec, and the data of Battat et al.[55] from 3.6×10^6 to 10^8 sec gives a total of 6.57 MeV per fission.

Summing the Zigman and Mackin data[50] from 1 sec to 1.8×10^4 sec and the Battat et al. data from 1.8×10^4 to 10^8 sec gives 6.35 MeV per fission. Both values are at least 2 MeV per fission less than the value obtained by inclusion of the Petrov data,[59] rather than the Zigman and Mackin data.[50] Because of the rather good agreement between the integrated results obtained above with the 6.65 MeV per fission obtained by Holden et al.[52] for the energy released from 1 to 10^8 sec after fission, we take this latter value and assign to it an uncertainty of ±20%.[3,63] For times $>10^8$ sec after fission, a value of 0.032 MeV per fission calculated by James[3] is used.

Summing the values given in Table 3 for times $>10^{-3}$ sec gives a value of $\overline{E}_{\gamma d}$ equal to 7.20 ± 1.3 MeV per fission. Bunney and Sam[66] find little difference in the number of photons with energies >0.065 MeV emitted in the fission of ^{235}U induced by thermal or fission spectrum neutrons from 900 to 7200 sec after fission. For longer times up to 2.6×10^5 sec (3 days), the number of photons emitted in thermal-neutron fission is consistently less than the number emitted in fission induced by fission spectrum neutrons. This is shown in Fig. 6 by the open and solid diamonds. The number of photons emitted after fission of ^{238}U by fission spectrum neutrons is similar to the number emitted by ^{235}U fission spectrum neutrons.[67]

In the fission of ^{239}Pu by neutrons, integration of normalized data of Walton and Sund[48,49] and Berick et al.[53] gives a gamma-ray energy release in the time from 10^{-3} to 0.2 sec of 0.10 ± 0.05 MeV per fission. (Integration from 10^{-3} to 1 sec gives 0.45 MeV per fission.) From 0.2 to 45 sec after fission, Fisher and Engle[54] report an energy release of 2.86 ± 0.71 MeV per fission. This is 11% lower than the energy released by delayed gamma rays from the fission of ^{235}U and is consistent with the report of Leipunsky et al.[68] that from 1.25 to 17 sec after fission the kinetics of decay of the gamma activity are the same for ^{235}U and ^{239}Pu, within the limits of experimental accuracy. Petrov,[59] who measured the energy released, as well as the kinetics of decay of the gamma rays, reported that both were the same within an experimental accuracy of 10%. The measurements of Petrov extend to 11 hr after fission. Integration of the Petrov data from 45 to 200 sec after fission gives an energy release of 1.36 MeV per fission. Since the energy release determined from the Petrov data appears to be too large for the ^{235}U data, and since ^{239}Pu energy-emission rates are smaller in the millisecond and second range than those of ^{235}U, the value of 1.36 MeV per fission is probably too large. Therefore the data of Zigman and Mackin[50] for ^{235}U were integrated over the same time range and gave an energy release of 0.99 MeV per fission. A 25% error is assigned to this value (see Table 6).

Since the calculated results of Battat et al.[55] for ^{235}U agree well with the experimental results for times >200 sec, their results for ^{239}Pu were integrated from 200 to 10^8 sec to give an energy release of 2.46 MeV. An uncertainty of 25% is also assigned to this value. Johnston[69] has reported calorimetric measurements of the energy released by beta particles and

gamma rays from approximately 40 to 150 days after fission of ^{239}Pu by fast neutrons. Integrating his results for gamma radiations over this time region gives an energy release of 0.068 MeV per fission. The data of Battat et al.[55] give 0.081 MeV per fission over the same interval of time, indicating reasonable agreement between the experimental and calculated results. The value of 0.03 MeV per fission is used[3] for the energy released during time $>10^8$ sec.

Summing the energy releases for the various times after fission gives an average total energy of 6.44 ± 0.98 MeV per fission for $\overline{E}_{\gamma d}$. This agrees well with the value of 6.3 ± 1.4 MeV per fission derived by James[3] based on the effective chain lengths, which are the mean number of decays required to reach the hypothetical line of beta stability, for ^{235}U and ^{239}Pu.

Fisher and Engle[54] have measured the energies released by photons from 0.2 to 45 sec following the fission of ^{232}Th, ^{233}U, and ^{238}U as well as ^{235}U and ^{239}Pu. The experimental results for these nuclides are given in Table 8. If the energy released by gamma rays after the first 45 sec is considered to be the same for all nuclides, then by combining the energy determined for ^{235}U neutron-induced fission with the results of Fisher and Engle,[54] one arrives at values of $\overline{E}_{\gamma d}$ for the various nuclides measured.[3] These extrapolated values of $\overline{E}_{\gamma d}$ are given in the third column of Table 8. (A value of 0.1 MeV per fission is assumed to be released from 1 msec to 0.2 sec by each nuclide.) The value of $\overline{E}_{\gamma d}$ given in Table 8 may be compared with the values of $\overline{E}_{\gamma d}$ determined from the effective chain lengths of the various nuclides as described in Appendix A. Remember that the extrapolated values of $\overline{E}_{\gamma d}$ are for fission induced by a spectrum of energies for which $\overline{E}_i$ is 1.47 MeV. The calculated values of $\overline{E}_{\gamma d}$ are given for either thermal neutron or for fission spectrum neutrons whose average energy E_i differs somewhat from 1.47 MeV.

TABLE 8. Experimental,[a] Extrapolated, and Calculated[b] Values for Delayed Gamma-radiation Energy from Fission Induced by a GODIVA Neutron Spectrum

Nuclide	Experimental Results, 0.2-45 sec, MeV/fission	$\overline{E}_{\gamma d}$ (extrapolated), MeV/fission	$\overline{E}_{\gamma d}$ (calculated), MeV/fission
^{232}Th	5.04 ± 0.71	9.0 ± 1.5	9.4
^{233}U	1.97 ± 0.28	5.9 ± 1.3	5.5
^{235}U	3.18 ± 0.45	7.1 ± 1.3	7.2
^{238}U	5.08 ± 0.71	9.0 ± 1.5	10.3
^{239}Pu	2.86 ± 0.71	6.8 ± 1.5	6.2

[a]Reference 54.

[b]Calculated from the square of the effective beta-decay chain lengths relative to $\overline{E}_{\gamma d}$ for ^{235}U (see Appendix A).

3.4 Beta Particle ($\bar{E}_\beta$) and Antineutrino Energies ($\bar{E}_{\bar{\nu}}$)

The total energy $\bar{E}_\beta$ associated with beta particles from fission is poorly known. Only a few measurements have been performed for thermal-neutron fission of ^{235}U, and poor agreement exists among the various measurements.[70-77] The experimental results of these measurements (as given by the respective authors) are presented in column 3 of Table 9. Recently Story has made several critical and thorough reevaluations of the existing data.[61,78] The results of one such reevaluation have been reported in the paper of James[3] and are reproduced here in column 4 of Table 9. A more recent and unpublished examination by Story[78] is summarized in column 5. The various experiments were reexamined during the present work, and we have chosen to apply relative weighting factors which reflect our relative confidence in the experimental values and the values obtained by Story.

TABLE 9. Total Beta-particle Energy for Thermal Fission of ^{235}U

Authors	Ref.	Authors' Quoted Values	Story Analysis Reported in James[3]	More Recent Story Analysis[78]	Value Used Here	Relative Weight
Muehlhause and Okeksa (1957)	70	~9		6.95 ± 0.75	6.95	1
Carter et al. (1959)	71	None	7.1 ± 0.6	7.22 ± 0.54	7.22	1
Armbruster and Meister (1962)	72	8.1 ± 0.4	7.75 ± 0.28	7.65 ± 0.33	7.65	3
Häring (1964)	73	8.6 ± 0.4				0
McNair et al. (1965)	74	None	6.73 ± 0.35	6.89 ± 0.34	6.63	2
MacMahon et al. (1969)	75	6.3 ± 0.5	6.3 ± 0.5	6.37 ± 0.5		
Kutcher and Wyman (1966)	76	None		7.33 ± 0.65	7.73	3
Tsoulfanides (1968)	77	7.73 ± 0.15				
Average		7.95[a]	6.97[a]	7.07[a]	7.36[b]	
Average deviation		±0.8	±0.4	±0.3	±0.4	

[a]Arithmetic average.
[b]Weighted average.

The experiments of Muehlhause and Oleksa[70] involve the measurement of the equilibrium beta spectrum for energies ≥0.5 MeV. The results of the beta-spectrum measurements are simply given by the authors of Ref. 70 in a figure and an analytical fit to their data. (The fit is in rather poor agreement with their experimental data for low beta energies, where the yield is the greatest.) The authors concluded that "the average energy per beta...is approximately 1.5 MeV which indicates an average beta energy per fission of about 9 MeV."

The work of Carter et al.[71] consisted of a beta-spectrum measurement for energies greater than 1 MeV before secular equilibrium had been achieved. By numerical integration of the measured spectrum, applying a correction for low-energy tailing and normalizing the data to 6.04 ± 0.05 betas/fission,[3] Story has arrived at a final value of ~7.2 MeV/fission.[61,78]

The work of Armbruster and Meister[72] consisted of a mass separation of the fission products followed by measurement of the number and energy of the beta particles ($E_\beta > 140$ keV) emitted to 3000 sec after fission. These results were then corrected to infinite time. Their initial value for the beta-particle energy per fission was 8.1 ± 0.4 MeV. However, Armbruster and Meister noted that the number of beta particles per fission measured in their work was too large. Assuming that the fission rate in these experiments may have been underestimated, Story[78] has reduced the measured beta-particle energy release integrated to 3000 sec by a factor of 14.6%. This factor represents the difference between (1) the number of beta particles per fission measured in the first 3000 sec after fission by Armbruster and Meister and (2) the expected value based on the measured time dependence of beta-particle emission and a total value of 6.04 beta particles emitted per fission.[3]

The high value of 8.6 ± 0.4 MeV per fission obtained by Häring[73] is difficult to interpret, since the absolute accuracy that can be achieved by the thermoluminescence-dosimetry method used in the measurement has not been adequately demonstrated. Consequently, this result has not been included in our analysis or in the previous analyses by James[3] and Story.[61,78]

The time-dependent beta-ray spectra reported by McNair et al.[74] have been reexamined and extrapolated to infinite irradiation and zero decay time by Story,[61,78] yielding the values given in Table 9. The experimental value of 6.3 ± 0.5 MeV per fission given by MacMahon et al.[75] is not an independent and absolute measurement, but was obtained[79] from a relative comparison of their data with the data of McNair et al.[74] using the value of 6.8 ± 0.5 MeV per fission obtained by reexamination of the McNair et al. data by McNair and Story.[61,78,79] Because of the interdependence of these two sets of data, a single arithmetic average has been used to represent the results of these measurements.

Kutcher and Wyman[76] measured the time dependence of the beta spectrum greater than 0.75 MeV, but did not quote a value for the total beta energy per fission. Recently, Tsoulfanides[77] (a student of Wyman's) has measured the time dependence of the beta spectrum from 0.1 to 1 MeV. Combining this data with that of Kutcher and Wyman,[76] Tsoulfanides obtained a value of 7.73 ± 0.15 MeV per fission. Since this result is based on a more complete set of data, we have used this value rather than the extrapolation of the Kutcher and Wyman data by Story.[61,78]

The present analysis gives a value of 7.36 ± 0.4 MeV per fission for the average beta-particle energy in thermal-neutron-induced fission of ^{235}U. From Table 9, it can be noted that this value is slightly higher than the two previous analyses by Story (6.97 ± 0.4 and 7.07 ± 0.3 MeV per fission).

The total antineutrino energy for ^{235}U fission can be estimated from this value of the total beta-particle energy and the beta-decay chain length

(the number of beta emissions required to reach stability). Using the average beta-decay chain length of 5.98 ± 0.2 beta-particles per fission for ^{235}U measured by Seyfarth,[80] the average beta-particle energy per fission is calculated to be 1.237 MeV. From the tables of Widman et al.,[81] the ratio $\bar{E}_\beta/(\bar{E}_\beta + \bar{E}_{\bar{\nu}})$ can be obtained, assuming the beta-particle spectrum to have an allowed shape and the average nuclear charge of the fragments to be 47.5. The average antineutrino energy per beta decay is then 1.74 MeV, and the total antineutrino energy per fission is 10.4 ± 0.6.

The error incurred using this most simple assumption, i.e., constant beta-particle energy for all members of the beta-decay chain, can be reduced by a more realistic assumption regarding the energies of the individual beta-particle decays within a chain. Ignoring pairing effects, nuclear isobaric masses are proportional to the factor $[Z(A) - Z_s(A)]^2$, where $Z(A)$ is the atomic number of the isobar in question and $Z_s(A)$ is the hypothetical most stable atomic number for that mass number A. The total energy release $\bar{E}_{\beta T}(A)$ for beta decay from one fragment in fission with mass A and formed with an initial most probable charge $Z_p(A)$ is then given approximately by

$$\bar{E}_{\beta T}(A) = \bar{E}_\beta(A) + \bar{E}_{\bar{\nu}}(A) + \bar{E}_{\gamma d}(A) \propto [Z_p(A) - Z_s(A)]^2$$

$$\simeq [\bar{N}_\beta(A)]^2 \simeq \left(\frac{\bar{N}_{\beta T}}{2}\right)^2. \qquad (19)$$

The quantity $\bar{N}_\beta(A)$ represents the average beta-decay chain length per fission fragment. The assumption is made that the beta-decay chain lengths of both fragments are equal ($\frac{1}{2}\bar{N}_{\beta T}$). The total beta-decay chain lengths, $\bar{N}_{\beta T}$, are calculated in Appendix A. Since $\bar{E}_{\gamma d}(A)$ is approximately proportional to $\bar{N}^2_{\beta T}$ (see Appendix A) and $\bar{E}_{\bar{\nu}}(A)$ is approximately proportional to $\bar{E}_\beta(A)$, then $\bar{E}_\beta(A)$ is expected to be approximately proportional to $\bar{N}^2_{\beta T}$. The beta-particle energy $\bar{E}_\beta(A,Z)$ for the isobar with charge Z can be calculated, as an example for integral values of $\bar{N}_\beta(A)$, knowing the total beta energy $\bar{E}_\beta(A)$ per fragment ($\bar{E}_\beta(A) \simeq \frac{1}{2}\bar{E}_\beta$):

$$\bar{E}_\beta(A,Z) \simeq \frac{[2(Z - Z_s) - 1]\,\bar{E}_\beta(A)}{2(1 + 3 + \ldots[2\bar{N}_\beta(A) - 1])} \qquad (20)$$

Using this formalism and the tables of Widman et al.,[81] we can estimate the average antineutrino energy for each member of this beta chain. The total antineutrino energy obtained in this manner is 10.26 ± 0.6 MeV. The close agreement between the results of this method and that obtained using the assumption of constant beta-particle energy simply illustrate the insensitivity of the various assumptions. The results obtained with the latter assumption are adopted in this work.

Because of the lack of information for $\overline{E}_\beta$, $\overline{E}_{\overline{\nu}}$, and $\overline{E}_{\gamma d}$ for fissioning systems other than ^{235}U, we have assumed that these values are simply proportional to the calculated $\overline{N}^2_{\beta T}$ values and have computed these values relative to those obtained for ^{235}U. The results of such a calculation for the beta-particle energies and antineutrino energies are summarized in Table 10.

TABLE 10. Average Energies Associated with Beta Particle and Antineutrinos Calculated Relative to ^{235}U

Target Nuclide	$\overline{E}_\beta$	$\overline{E}_{\overline{\nu}}$	Target Nuclide	$\overline{E}_\beta$	$\overline{E}_{\overline{\nu}}$
^{232}Th	9.5 ± 0.5	13.3 ± 0.8	^{239}Pu	6.3 ± 0.3	8.8 ± 0.5
^{233}U	5.6 ± 0.3	7.8 ± 0.5	^{240}Pu	7.2 ± 0.4	10.1 ± 0.6
^{235}U	7.36 ± 0.4	10.26 ± 0.6	^{241}Pu	8.2 ± 0.4	11.5 ± 0.7
^{238}U	10.5 ± 0.6	14.7 ± 0.9	^{242}Pu	9.3 ± 0.5	12.9 ± 0.8

4. CALCULATION OF Q_f' FROM INDIVIDUAL CONTRIBUTIONS

The total energy released directly from the fission process has been calculated using the previously given individual contributions (Sects. 3.1-3.4) and Eq. 3. The results of this calculation are summarized in Table 11. Table 12 compares the results for the calculation of Q_f' from this work with the results of James.[3] The present work yields results that are consistently higher (an average of 1.4 MeV) than those given by James. This difference is principally due to the higher value used in this work for the average beta-particle energy for ^{235}U (see Sect. 3.4). Since the beta-particle and antineutrino energies for the other fissioning systems have been calculated relative to the assumed value for the beta-particle energy of ^{235}U, use of a larger value for this quantity will lead directly to larger values for all the other beta-particle and antineutrino energies.

TABLE 11. Total Energy Released Directly from Fission, Q_f', Calculated by Summation of the Individual Contributions (Eq. 7)

Target Nuclide	Neutron Energy Spectrum	$\overline{E}_{Kf}$	$\overline{E}_n$	$\overline{E}_{\gamma p}$	$\overline{E}_{\gamma d}$	$\overline{E}_\beta$	$\overline{E}_{\overline{\nu}}$	$\overline{E}_i$[a]	Q_f'
^{232}Th	FN	160.0 ± 2.0	4.49 ± 0.17	7.6 ± 1.5	9.0 ± 1.5	9.5 ± 0.5	13.3 ± 0.8	3.0	200.9 ± 3.1
^{233}U	T	167.5 ± 2.0	4.90 ± 0.15	7.6 ± 1.5	5.9 ± 1.3	5.6 ± 0.3	7.8 ± 0.5	0	199.3 ± 2.9
^{235}U	T	167.9 ± 2.0	4.69 ± 0.11	7.64 ± 0.75	7.1 ± 1.3	7.4 ± 0.4	10.3 ± 0.6	0	205.0 ± 2.6
^{238}U	FN	165.9 ± 2.0	5.60 ± 0.16	7.6 ± 1.5	9.0 ± 1.5	10.5 ± 0.6	14.7 ± 0.9	2.8	210.5 ± 3.1
^{239}Pu	T	174.0 ± 2.0	5.87 ± 0.11	8.01 ± 0.94	6.8 ± 1.5	6.3 ± 0.3	8.8 ± 0.5	0	209.8 ± 2.7
^{241}Pu	T	175.6 ± 2.0	5.85 ± 0.15	7.6 ± 1.5[b]	7.9 ± 1.5[b]	8.2 ± 0.4	11.5 ± 0.7	0	216.6 ± 3.0

[a] $\overline{E}_i = \dfrac{\int_0^\infty E \cdot N(E)\sigma_f(E)\,dE}{\int_0^\infty N(E)\sigma_f(E)\,dE}$, where N(E) is given in Fig. 3 and $\sigma_f(E)$ represents the fission cross section as a function of neutron energy.

[b] Calculated relative to ^{235}U assuming $\overline{E}_{\gamma d} \propto \overline{N}^2_{\beta T}$.

TABLE 12. Comparison of Q_f' Determined by Summation of Individual Contributions in This Work with the Results of James[3]

Target Nuclide	Q_f' from Present Work, MeV	Q_f' from James,[3] MeV	Diff, MeV
^{232}Th	200.9 ± 3.1	None	
^{233}U	199.3 ± 2.9	None	
^{235}U	205.0 ± 2.6	204.4 ± 3.5	+0.6
^{238}U	210.5 ± 3.1	208.6 ± 5.0	+1.9
^{239}Pu	209.8 ± 2.7	208.9 ± 3.9	+0.9
^{241}Pu	216.6 ± 3.0	214.5 ± 4.4	+2.1
		Average difference	+1.38

5. COMPARISON OF Q_f' VALUES COMPUTED FROM MASS EXCESSES AND SUMMATION OF INDIVIDUAL CONTRIBUTIONS

Table 13 compares the values of Q_f' calculated using the mass-excess formalism (see Sect. 2) with the values obtained by summing the individual contributions (see Sect. 3). From this comparison, two observations can be made. First, the errors in the determination of Q_f' by means of the mass-excess formalism are an order of magnitude smaller than the errors associated with Q_f' calculated by summation of the individual contributions. Second, the values of Q_f' obtained by the latter method are on the average 3.5 MeV larger than those calculated from the mass excesses. This difference is slightly greater than the estimated errors. The source of this discrepancy is not known at this time. However, because of the lack of data for the energies of beta particles and antineutrinos for all the fissioning system and the approximations used in this work to estimate these values, these energies are the most questionable. Also, if the double-velocity data for the fragment-kinetic energies (see Sect. 3.1) are in actuality correct and the double-energy measurements incorrect, then the difference in Q_f' calculated by the two methods is reduced to -1.5 MeV, well within the quoted errors.

TABLE 13. Comparison of Q_f' Calculated from Mass Excesses with That Calculated by Summation of Individual Contributions

Target Nuclide	Neutron Energy Spectrum	Q_f' from Mass Excesses (Sect. 2), MeV	Q_f' from Summation of Individual Contributions, MeV	Diff in Q_f'
^{232}Th	FN	196.37 ± 0.35	200.9 ± 3.1	-4.53 ± 3.1
^{233}U	T	197.99 ± 0.21	199.3 ± 2.9	-1.31 ± 2.9
^{235}U	T	202.74 ± 0.21	205.0 ± 2.6	-2.26 ± 2.6
^{238}U	FN	205.89 ± 0.45	210.5 ± 3.1	-4.61 ± 3.1
^{239}Pu	T	207.16 ± 0.21	209.8 ± 2.7	-2.64 ± 2.7
^{241}Pu	T	210.92 ± 0.22	216.6 ± 3.0	-5.68 ± 3.0
			Average difference	-3.5

Because of the discrepancies in the values of Q_f' determined by the two methods of calculation, the values obtained using the mass-excess

formalism (see Sect. 2) with their inherently much smaller errors are judged to be more correct and are used in later sections of this report. Also, in light of possible errors in the determination of Q_f' by summation of the individual contributions, systematic errors (larger than the errors given) are indicated to be present in one or more of the component energies, and caution should be exercised in the usage of these values.

6. TOTAL ENERGY ABSORBED IN A REACTOR

Using Eqs. 8 and 9, values of Q_{eff} and Q_T have been calculated and are presented in Table 14. In the calculation of these quantities, (1) the values of Q_f' determined from the mass-excess formalism (see Sect. 2) have been used; (2) $\Delta\overline{E}_{\gamma d}$ and $\Delta\overline{E}_{\beta}$ are assumed to be equal to zero; i.e., the heat produced is integrated to infinite time; and (3) Q_c (see Appendix B) and hence Q_T are calculated for a specific reactor core configuration and composition. These latter values are therefore only approximate for other types of cores. Approximate corrections to the values of Q_{eff} and Q_T for reactor operations covering finite lengths of time are given in Table 15. These corrections were obtained from the average fission-product mass excesses computed for various times after fission given in Table 1 and assuming that 59% of the total energy associated with beta decay ($\overline{E}_{\overline{\nu}}+\overline{E}_{\gamma d}+\overline{E}_{\beta}$) is attributable to beta particles and gamma rays

TABLE 14. Summary of Q_{eff} and Q_T

Target Nuclide	Neutron Energy	Q_f' [a]	$\overline{E}_{\nu}$ [b]	Q_c [c]	$Q_{eff}(\infty)$	$Q_T(\infty)$
^{232}Th	FN	196.37 ± 0.35	13.3 ± 0.8	8.88 ± 0.5	183.1 ± 0.9	192.0 ± 1.0
^{233}U	T	197.99 ± 0.21	7.8 ± 0.5	9.71 ± 0.3	190.2 ± 0.5	200.0 ± 0.6
^{235}U	T	202.74 ± 0.21	10.3 ± 0.6	9.29 ± 0.3	192.4 ± 0.6	201.7 ± 0.7
^{238}U	FN	205.89 ± 0.45	14.7 ± 0.9	11.82 ± 0.5	191.2 ± 1.0	203.0 ± 1.1
^{239}Pu	T	207.16 ± 0.21	8.8 ± 0.5	12.26 ± 0.4	198.4 ± 0.5	210.6 ± 0.7
^{240}Pu	FN	206.4 ± 1.6	10.1 ± 0.6	14.17 ± 1.4	196.3 ± 1.7	210.5 ± 2.2
^{241}Pu	T	210.92 ± 0.22	11.5 ± 0.7	12.63 ± 0.4	199.4 ± 0.7	212.0 ± 0.8
^{242}Pu	FN	210.8 ± 3.2	12.9 ± 0.8	14.24 ± 2.6	197.9 ± 3.3	212.1 ± 4.2

[a]See Table 1.
[b]See Table 10.
[c]See Table 24; $Q_c = (\overline{\nu}_T - 1)Q_{nc}$, Q_{nc} = 6.53 ± 0.2 MeV per captured neutron.

TABLE 15. Approximate Corrections to $Q_{eff}(\infty)$ and $Q_T(\infty)$ for Finite Time Integration of Heat from Fission

Heat Integration Time after Fission	Correction, MeV	Heat Integration Time after Fission	Correction, MeV
30 days	-0.47	100 yr	-0.003
1 yr	-0.23	∞	0

which contribute heat to the reactor. As can be seen from Table 15, the corrections that must be applied for long-lived beta and gamma activity are relatively small for integrating times >30 days. However, for shorter times this correction becomes important and should be calculated accurately.

7. DEPENDENCE OF ENERGY RELEASE ON INCIDENT NEUTRON ENERGY

7.1 Dependence of Energy Release on Incident Neutron Energy from Mass-excess Calculations

The total energy absorbed in a reactor per fission event (in the mass-excess calculation formalism; see Sect. 2) is given as

$$Q_T = m(A,Z) - \sum_i Y_i m(A_i,Z_i) - (\bar{\nu}_T - 1)\, m_n - \bar{E}_{\bar{\nu}} + (\bar{\nu}_T - 1)\, Q_{nc} - \Delta\bar{E}_{\gamma d} - \Delta\bar{E}_{\beta}, \tag{21}$$

where Q_{nc} is the average energy released by capture of one fission neutron in the reactor materials and subsequent beta-particle and gamma-ray emission of the neutron capture products. An illustration of the calculation of Q_{nc} is given in Appendix B. Differentiating with respect to the incident neutron energy, E_i, and assuming $\Delta\bar{E}_{\gamma d}$ and $\Delta\bar{E}_{\beta}$ to be independent of E_i, we obtain

$$\frac{dQ_T}{dE_i} = \frac{-d}{dE_i}\left[\sum_i Y_i m(A_i,Z_i)\right] - m_n \frac{d\bar{\nu}_T}{dE_i} - \frac{d\bar{E}_{\bar{\nu}}}{dE_i} + Q_{nc}\frac{d\bar{\nu}_T}{dE_i} + (\bar{\nu}_T - 1)\frac{dQ_{nc}}{dE_i}. \tag{22}$$

The first term cannot be directly evaluated. However, an approximate estimate of this quantity can be obtained from the computed average mass excesses given in Table 1 for ^{235}U and ^{238}U for various incident neutron energies. Values of

$$\frac{d}{dE_i}\left[\sum_i Y_i m(A_i,Z_i)\right] = -0.064 \text{ and } -0.037$$

were obtained for ^{235}U and ^{238}U, respectively. The approximate values for this term are more than an order of magnitude smaller than the terms involving the factor $d\bar{\nu}_T/dE_i$. Hence, this term is relatively unimportant. Because of the lack of more detailed information, the value obtained for ^{235}U was assumed to be applicable to the other fissioning systems. The second and fourth terms on the right-hand side of Eq. 22, involving the factor $d\bar{\nu}_T/dE_i$, can be evaluated directly by using the reported values for this

quantity. In this work, we have used the values of $d_{\overline{\nu}T}/dE_i$ given by Fillmore.[37] The last factor, involving the dependence of the (n,γ) neutron capture energy release on incident neutron energy (dQ_{nc}/dE_i), is difficult to estimate, since this calculation requires detailed knowledge of the composition of the reactor and the neutron spectrum and entails detailed integrations over the energy-dependent (n,γ) capture cross sections for all the isotopes present in the reactor. Such a detailed calculation is outside the scope of this report. However, since the energy dependence of the (n,γ) cross sections for the major contributors are somewhat similar for $E_i > 100$ keV, the neutron inventory (see Appendix B) and hence Q_{nc} are not expected to change drastically for small changes of E_i. Consequently, in lieu of detailed calculations, it is assumed that $dQ_{nc}/dE_i \approx 0$.

The third factor, involving the dependence of the antineutrino energy on incident neutron energy, is difficult to estimate and can only be approximated here. It is assumed, as earlier, that the antineutrino energy is proportional to the square of the beta-decay chain length. That is,

$$\overline{E}_{\overline{\nu}} = K\overline{N}^2_{\beta T} \tag{23}$$

Differentiating with respect to E_i, one obtains

$$\frac{d\overline{E}_{\overline{\nu}}}{dE_i} = 2K\overline{N}_{\beta T}\frac{d\overline{N}_{\beta T}}{dE_i}. \tag{24}$$

For low-energy neutron-induced fission, it can be assumed that the charge-division parameter Δ (see Appendix A) is the same as for thermal-neutron fission. Then the change in beta-decay chain length with increasing E_i is directly related to the change in prompt-neutron emission. For one fragment,

$$\overline{N}_\beta(A_f) \simeq Z_s(A_f) - \overline{Z}_p(A_f). \tag{25}$$

The most probable final mass A_f is the result of the emission of $\overline{\nu}(A_f)$ neutrons from the initial mass A_i, where $A_i = A_f + \overline{\nu}(A_f)$. Since the nuclear charge does not change during neutron emission,

$$\overline{Z}_p(A_f) \simeq \overline{Z}_p(A_i) \simeq \overline{Z}_p[A_f + \overline{\nu}(A_f)],$$

neglecting the dispersion about $\overline{\nu}(A)$. Therefore,

$$\overline{N}_\beta(A_f) \simeq Z_s(A_f) - \overline{Z}_p[A_f + \overline{\nu}(A_f)]. \tag{26}$$

The difference in beta-decay chain length for this fragment in going from neutron energy E_1 and E_2, assuming

$$Z_p(A) = \frac{Z_F}{A_F} A \pm \Delta$$

(see Appendix A), is then

$$\Delta\overline{N}_\beta(A_f) = \overline{Z}_p[A_f + \overline{\nu}(A_f,E_1)] - \overline{Z}_p[A_f + \overline{\nu}(A_f,E_2)]$$

$$= \frac{Z_F}{A_F} \{A_f + \overline{\nu}(A_f,E_1) - [A_f + \overline{\nu}(A_f,E_2)]\}$$

$$= \frac{Z_F}{A_F} [\overline{\nu}(A_f,E_1) - \overline{\nu}(A_f,E_2)]. \tag{27}$$

The change in total beta-decay chain length (summing contributions for both fragments) can then be expressed as

$$\Delta\overline{N}_{\beta T}(A_f) = \Delta\overline{N}_\beta(A_f) + \Delta\overline{N}_\beta(A_F - A_f)$$

$$\simeq \frac{Z_F}{A_F} [\overline{\nu}_T(A_f,E_1) - \overline{\nu}_T(A_f,E_2)], \tag{28}$$

from which one derives

$$\frac{d\overline{N}_{\beta T}}{d\overline{\nu}_T} = -\frac{Z_F}{A_F} \tag{29}$$

and

$$\frac{d\overline{N}_{\beta T}}{dE_i} = \frac{d\overline{N}_{\beta T}}{d\overline{\nu}_T}\frac{d\overline{\nu}_T}{dE_i} = -\frac{Z_F}{A_F}\frac{d\overline{\nu}_T}{dE_i}. \tag{30}$$

The accuracy of this approximation (see Eq. 30) can be tested for ^{235}U by using the beta-decay chain lengths given in Table 1, which were calculated from the mass-yield distributions obtained for three incident neutron energies (thermal, fission spectrum, and 14 MeV) and the value of $d\overline{\nu}_T/dE_i$ given by Fillmore.[37] For ^{235}U, $d\overline{N}_{\beta T}/dE_i = -0.061$ from Eq. 30, and from the data in Table 1, the value of -0.063 is obtained. The agreement is quite good considering the approximate nature of Eq. 30 and the calculated beta-decay chain lengths of Table 1.

If Eq. 30 is substituted into Eq. 24, the dependence of antineutrino energy or incident neutron energy can be approximated by

$$\frac{d\overline{E}_{\overline{\nu}}}{dE_i} = -2K\overline{N}_{\beta T}\frac{Z_F}{A_F}\frac{d\overline{\nu}_T}{dE_i}. \tag{31}$$

The values obtained for the dependence of the total energy release on captured neutron energy as well as the calculation of individual terms of Eq. 22 are summarized in Table 16. From column 7, the energy released directly from the fission process Q_{eff} is almost inversely related to the captured neutron energy, the energy release decreasing by approximately 0.8 MeV for every 1-MeV increase in neutron energy. However, with the inclusion of the term $Q_{nc} d\overline{\nu}_T/dE_i$ for the energy released by (n,γ) capture of the fission neutrons, the total energy release is virtually independent of the captured neutron energy. Neglecting the term $(\overline{\nu}_T - 1)\, dQ_{nc}/dE_i$ in Eq. 22, the total energy release Q_T increases only ~0.04 MeV for every 1-MeV increase in neutron energy.

TABLE 16. Dependence of Energy Release on Incident Neutron Energy from Mass Excess Calculations

Target Nuclide	$\frac{d\overline{\nu}_T}{dE_i}$ (Ref. 37)	$\frac{d}{dE_i}\left[\sum_i Y_i m(A_i, Z_i)\right]$	$m_n \frac{d\overline{\nu}_T}{dE_i}$	$\frac{d\overline{E}_{\overline{\nu}}}{dE_i}$ [a]	$Q_{nc} \frac{d\overline{\nu}_T}{dE_i}$ [b]	$\frac{dQ_{eff}}{dE_i}$	$\frac{dQ_T}{dE_i}$ [c]
^{232}Th	0.1516 ± 0.0035	-0.064	1.224 ± 0.028	-0.229 ± 0.011	0.990 ± 0.038	-0.93 ± 0.03	0.06 ± 0.05
^{233}U	0.0412 ± 0.0119, $E_i < 1.08$	-0.064	0.333 ± 0.096	-0.048 ± 0.014	0.269 ± 0.078	-0.22 ± 0.10	0.05 ± 0.12
	0.1299 ± 0.0078, $E_i > 0.96$		1.0484 ± 0.063	-0.152 ± 0.013	0.848 ± 0.057	-0.83 ± 0.06	0.02 ± 0.09
^{235}U	0.1146 ± 0.0033, $E_i < 2.57$	-0.064	0.925 ± 0.027	-0.153 ± 0.009	0.748 ± 0.031	-0.71 ± 0.03	0.04 ± 0.04
	0.1569 ± 0.0037, $E_i > 2.44$		1.266 ± 0.030	-0.210 ± 0.012	1.025 ± 0.040	-0.99 ± 0.03	0.03 ± 0.05
^{238}U	0.1514 ± 0.0034	-0.037	1.222 ± 0.027	-0.239 ± 0.011	0.989 ± 0.038	-0.95 ± 0.03	0.04 ± 0.05
^{239}Pu	0.1275 ± 0.0044	-0.064	1.029 ± 0.036	-0.159 ± 0.010	0.833 ± 0.038	-0.81 ± 0.04	0.03 ± 0.05
^{241}Pu	0.1429 ± 0.0054	-0.064	1.153 ± 0.044	-0.201 ± 0.012	0.933 ± 0.045	-0.89 ± 0.05	0.05 ± 0.06

[a]Error includes estimated ±0.3 error in $\overline{N}_{\beta T}$.
[b]Q_{nc} values from Appendix B.
[c]Calculated for $(\nu_T - 1)\, dQ_{nc}/dE_i = 0$; refer to discussion in Sect. 7.1.

Because of the near cancelation of contributing terms to dQ_T/dE_i, the last factor in Eq. 22, $(\overline{\nu}_T - 1)\, dQ_{nc}/dE_i$, although anticipated to be small and assumed to be zero, may be of importance. Before a firm conclusion regarding dQ_T/dE_i is established, this term should be accurately calculated.

7.2 Variation of the Components of Total Energy with Incident Neutron Energy

Equation 3, which gives the average total energy released per fission, may be written as

$$Q_f = \overline{E}_K + \overline{E}_n + \overline{E}_{\gamma p} + \overline{E}_{\beta T}, \tag{32}$$

where

$$\overline{E}_{\beta T} = \overline{E}_\beta + \overline{E}_{\gamma d} + \overline{E}_{\overline{\nu}}. \tag{33}$$

In this section we investigate the variation of each of the components given in Eq. 32 as a function of the incident neutron energy E_i. The approach to the problem is essentially that of James.[3]

7.2.1 Fission Fragments

Terrell[39] has determined the average fragment kinetic energy per nucleon to be 0.75 ± 0.02 MeV. This implies that each neutron emitted reduces the fragment kinetic energy by this amount, or

$$\bar{E}_{Kf} \simeq \bar{E}_{Ki} - (0.75 \pm 0.02)\,\bar{\nu}_p. \tag{34}$$

The change in $\bar{E}_{Kf}$ with incident neutron energy is therefore

$$\frac{d\bar{E}_{Kf}}{dE_i} \simeq \frac{d\bar{E}_{Ki}}{dE_i} - (0.75 \pm 0.02)\,\frac{d\bar{\nu}_p}{dE_i}. \tag{35}$$

There have been a number of measurements of the variation $\bar{E}_{Ki}$ with E_i, primarily for ^{235}U, ^{233}U, ^{238}U, and ^{232}Th. Early measurements[82-85] with ^{235}U and ^{233}U indicated that $\bar{E}_{Ki}$ fluctuates with E_i to about E_i = 1 MeV. However, recent measurements with ^{235}U indicate that the fluctuations are not nearly as great as those reported earlier[86,87] or that they may not even exist.[88] Present information concerning ^{233}U indicates that E_{Ki} increases initially with E_i to $E_i \simeq 2$ MeV.[83-86] Table 17 lists approximate values of $d\bar{E}_{Ki}/dE_i$ at various values of E_i derived from data available for ^{235}U (Refs. 82, 83, 85-90), ^{233}U (Refs. 83-86 and 89), ^{238}U (Refs. 89 and 91-93), and ^{232}Th (Refs. 91, 93, 94). The uncertainties in the values of $d\bar{E}_{Ki}/dE_i$ are rather large. However, the value of 0 ± 0.2 assumed by James[3] for ^{235}U appears reasonable for that nuclide. Since $d\bar{E}_{Ki}/dE_i$ varies with both E_1 and target nucleus, it is misleading to assign values to those nuclides for which measurements have not been made.

TABLE 17. Approximate Values of $d\bar{E}_{Ki}/dE_i$ at Various Values of E_i Derived from Experimental Data

Nuclide	E_i, MeV				References
	0	2	5	15	
	$d\bar{E}_{Ki}/dE_i$				
^{235}U	0	0	-0.1	-0.2	82, 83, 85-89
^{233}U	0.6	0.05	-0.2	-0.2	83-86, 89
^{238}U		-0.18	-0.23	-0.3	91, 93
^{238}U		0	0	-0.4	89, 92
^{232}Th		1	0	-0.8	91, 94, 95

The variation of $\bar{\nu}_p$ with E_i has been investigated extensively. Fillmore[37] has made a weighted least-squares linear fit to the data. Values of the slope of the straight line corresponding to $d\bar{\nu}_p/dE_i$ are given in Table 18.

Approximate calculation of $d\bar{E}_{Ki}/dE_i$ may be made at various incident neutron energies by substituting the data given in Tables 17 and 18 into Eq. 35. For example, $d\bar{E}_{Ki}/dE_i$ for ^{235}U in the range of 0 to 2 MeV neutrons is $(0 \pm 0.2) - (0.75 \pm 0.02)(0.1156 \pm 0.0033) = -0.086 \pm 0.2$ MeV per MeV.

TABLE 18. Values of $d\bar{\nu}_p/dE_i$ for Various Nuclides[a]

Nuclide	$d\bar{\nu}_p/dE_i$	Energy Range, E_i, MeV	Nuclide	$d\bar{\nu}_p/dE_i$	Energy Range, E_i, MeV
^{232}Th	0.1516 ± 0.0035		^{238}U	0.1514 ± 0.0034	
^{233}U	0.0412 ± 0.0119	<1.08	^{239}Pu	0.1275 ± 0.0044	
^{233}U	0.1229 ± 0.0079	>0.96	^{240}Pu	0.0925 ± 0.0144	
^{235}U	0.1146 ± 0.0033	<2.57	^{241}Pu	0.1429 ± 0.0054	
^{235}U	0.1569 ± 0.0037	>2.44	^{242}Pu	(0.0925)[b]	

[a]Data from Ref. 37.
[b]Assumed to be the same as ^{240}Pu.

7.2.2 Neutrons

The contribution of delayed neutrons to the total energy released is small, and its dependence on the incident neutron energy will be neglected.* The average neutron kinetic energy per fission is then

$$\bar{E}_n = \bar{\nu}_p B_p. \tag{36}$$

From Eq. 18,

$$B_p = (0.75 \pm 0.02) + (0.65 \pm 0.02)(\bar{\nu}_p + 1)^{1/2}.$$

Substituting this into Eq. 36 and differentiating with respect to E_i gives

$$\frac{d\bar{E}_n}{dE_i} = \left[(0.75 \pm 0.02) + (0.325 \pm 0.01)\,\frac{3\bar{\nu}_p + 2}{(\bar{\nu}_p + 1)^{1/2}}\right]\frac{d\bar{\nu}_p}{dE_i}. \tag{37}$$

Values of $d\bar{E}_n/dE_i$ have been calculated from the data of Fillmore[37] for E_i = 2.0 and 5.0 MeV. These values are given in Table 19 for the various nuclides.

TABLE 19. Values of $d\bar{E}_n/dE_i$ Calculated for Various Nuclides at E_i = 2.0 and 5.0 MeV

Nuclide	$d\bar{E}_n/dE_i$ 2.0 MeV	$d\bar{E}_n/dE_i$ 5.0 MeV	Nuclide	$d\bar{E}_n/dE_i$ 2.0 MeV	$d\bar{E}_n/dE_i$ 5.0 MeV
^{232}Th	0.349 ± 0.012	0.369 ± 0.012	^{239}Pu	0.328 ± 0.014	0.340 ± 0.014
^{233}U	0.318 ± 0.021	0.331 ± 0.022	^{240}Pu	0.239 ± 0.038	0.246 ± 0.039
^{235}U	0.279 ± 0.010	0.402 ± 0.014	^{241}Pu	0.371 ± 0.016	0.386 ± 0.017
^{238}U	0.370 ± 0.012	0.388 ± 0.013	^{242}Pu	0.239 ± 0.038[a]	0.246 ± 0.039[a]

[a]Assumed to be the same as ^{240}Pu.

7.2.3 Prompt Gamma Radiation

The measurements of Protopopov and Shiriaev[42,58] with ^{235}U and thermal, 2.8-, and 14.7-MeV neutrons and ^{238}U and 2.8- and 14.7-MeV

*It is interesting to note (see Table 3) that $\bar{\nu}_d$ apparently increases with E_i to some maximum value beyond 3.1 MeV and then decreases as E_i increases to 15 MeV.

neutrons indicate that, within an experimental accuracy of about 15%, the total energy of the prompt gamma rays is the same. We therefore assume

$$\frac{d\overline{E}_{\gamma p}}{dE_i} = 0 \pm 0.15. \tag{38}$$

7.2.4 Total Beta Decay

In Sect. 3.4, the following relationship was assumed:

$$\overline{E}_{\beta T} \propto \overline{N}^2_{\beta T}.$$

The total beta-decay energy for a given nuclide may then be calculated from the total beta-decay energy released in thermal neutron fission of ^{235}U,

$$\overline{E}_{\beta T}(A,Z,E_i) = \overline{E}_{\beta T}(^{235}U)\,\frac{\overline{N}^2_{\beta T}(A,Z,E_i)}{\overline{N}^2_{\beta T}(^{235}U)}. \tag{39}$$

Differentiating Eq. 39 with respect to incident neutron energy E_i gives

$$\frac{d\overline{E}_{\beta T}(A,Z,E_i)}{dE_i} = \frac{2\overline{E}_{\beta T}(^{235}U)}{\overline{N}^2_{\beta T}(^{235}U)}\,\overline{N}_{\beta T}(A,Z,E_i)\,\frac{d\overline{N}_{\beta T}(A,Z,E_i)}{dE_i} \tag{40a}$$

$$= 2\,\frac{24.82 \pm 1.5}{(5.98 \pm 0.2)^2}\,\overline{N}_{\beta T}(A,Z,E_i)\,\frac{d\overline{N}_{\beta T}(A,Z,E_i)}{dE_i} \tag{40b}$$

$$= (1.39 \pm 0.10)\,\overline{N}_{\beta T}(A,Z,E_i)\,\frac{d\overline{N}_{\beta T}(A,Z,E_i)}{dE_i} \tag{40c}$$

In Sect. 7.1, it was shown that

$$\frac{d\overline{N}_{\beta T}(A,Z,E_i)}{dE_i} \simeq -\frac{Z_F}{A_F}\,\frac{d\overline{\nu}_T}{dE_i}. \tag{41}$$

Substituting Eq. 41 into Eq. 40c gives

$$\frac{d\overline{E}_{\beta T}(A,Z,E_i)}{dE_i} = -(1.39 \pm 0.10)\,\frac{Z_F}{A_F}\,\overline{N}_{\beta T}(A,Z,E_i)\,\frac{d\overline{\nu}_T}{dE_i}. \tag{42}$$

Unfortunately, Eq. 42 requires knowledge of $\overline{N}_{\beta T}$ at energy E_i to give the change in $\overline{E}_{\beta T}$ with E_i. For small changes in E_i it may be assumed (see Sect. 7.1) that

$$\bar{N}_{\beta T}(A,Z,E_i) = \bar{N}_{\beta T}(A,Z,\text{thermal}) + \Delta\bar{N}_{\beta T}$$

$$= \bar{N}_{\beta T}(A,Z,\text{thermal}) + \frac{Z_F}{A_F}\left[\bar{\nu}_T(\text{thermal}) - \bar{\nu}_T(E_i)\right]. \qquad (43)$$

The designation "thermal" refers either to thermal-neutron energies for the fissile nuclides or to fission-spectrum neutron energies for the other nuclides.

Values of $\bar{E}_{\beta T}$ have been calculated for neutron energies of 2.0 and 5.0 MeV using Eqs. 42 and 43 and calculated values of $\bar{N}_{\beta T}$. These values are listed in Table 20 for various nuclides and are to be considered only rough approximations to the actual values.

TABLE 20. Calculated Values of $d\bar{E}_{\beta T}/dE_i$ for Various Nuclides at E_i = 2.0 and 5.0 MeV

Nuclide	$\bar{N}_{\beta T}$, Calculated	Z_F/A_F	$d\bar{E}_{\beta T}/dE_i$ 2.0 MeV	$d\bar{E}_{\beta T}/dE_i$ 5.0 MeV	Nuclide	$\bar{N}_{\beta T}$, Calculated	Z_F/A_F	$d\bar{E}_{\beta T}/dE_i$ 2.0 MeV	$d\bar{E}_{\beta T}/dE_i$ 5.0 MeV
^{232}Th	6.81	0.386	-0.56	-0.54	^{238}U	7.15	0.385	-0.58	-0.51
^{233}U	5.20	0.393	-0.36	-0.35	^{239}Pu	5.54	0.392	-0.38	-0.31
^{235}U	5.98	0.390	-0.37	-0.49	^{241}Pu	6.32	0.388	-0.48	-0.41

7.2.5 Q_f versus Incident Neutron Energy

Table 21 summarizes the variation of the various component energies and the total energy Q_f with incident neutron energy at 2.0 and 5.0 MeV

TABLE 21. Variation of Component Energies and Total Energy Q_f with Incident Neutron Energy E_i at 2.0 and 5.0 MeV for Several Nuclides

Nuclide	$\frac{d\bar{E}_{Ki}}{dE_i}$ [a]	$\frac{d\bar{E}_{Kf}}{dE_i}$	$\frac{d\bar{E}_n}{dE_i}$	$\frac{d\bar{E}_{\gamma p}}{dE_i}$	$\frac{d\bar{E}_{\beta T}}{dE_i}$ [b]	$\frac{dQ_f}{dE_i}$ [c]	$\frac{dQ_f}{dE_i}$ [d] (mass excess)
				E_i = 2.0 MeV			
^{232}Th	1 ± 0.5	0.9 ± 0.5	0.35 ± 0.02	0 ± 0.15	-0.56 ± 0.56	0.69 ± 0.8	-0.16 ± 0.04
^{233}U	0.05 ± 0.1	-0.04 ± 0.1	0.32 ± 0.03	0 ± 0.15	-0.36 ± 0.36	-0.08 ± 0.4	0.02 ± 0.07
^{235}U	0 ± 0.2	-0.09 ± 0.2	0.28 ± 0.02	0 ± 0.15	-0.37 ± 0.37	-0.18 ± 0.2	0.14 ± 0.04
^{238}U	-0.18 ± 0.4	-0.3 ± 0.4	0.37 ± 0.02	0 ± 0.15	-0.58 ± 0.58	-0.51 ± 0.7	-0.18 ± 0.04
				E_i = 5.0 MeV			
^{232}Th	0 ± 0.2	-0.11 ± 0.2	0.37 ± 0.03	0 ± 0.15	-0.54 ± 0.54	-0.28 ± 0.6	-0.16 ± 0.04
^{233}U	-0.2 ± 0.4	-0.29 ± 0.4	0.33 ± 0.06	0 ± 0.15	-0.35 ± 0.35	-0.31 ± 0.6	0.02 ± 0.07
^{235}U	-0.1 ± 0.2	-0.22 ± 0.2	0.40 ± 0.03	0 ± 0.15	-0.49 ± 0.49	-0.31 ± 0.6	-0.20 ± 0.04
^{238}U	-0.23 ± 0.5	-0.34 ± 0.5	0.39 ± 0.03	0 ± 0.15	-0.57 ± 0.57	-0.52 ± 0.8	-0.18 ± 0.04
^{239}Pu							0.04 ± 0.05
^{241}Pu							-0.09 ± 0.05

[a] Uncertainties equal to a factor of 2 are arbitrarily assigned to these values, with the exception of ^{232}Th.
[b] Uncertainties equal to a factor of 1 are arbitrarily assigned to these values.
[c] Summation of the individual contributions.
[d] Calculated from Eq. 44 assuming a 0.03 uncertainty in $\frac{d}{dE_i}\left[\sum_i Y_i m(A_i, Z_i)\right]$.

for the nuclides ^{232}Th, ^{233}U, ^{235}U, and ^{238}U. Only for ^{232}Th at 2.0 MeV does the total energy appear to increase with incident neutron energy E_i. However, the errors assigned to the various values of a Q_f/dE_i are so large as to preclude any definite conclusions.

Differentiation of Eq. 6 with respect to incident neutron energy gives

$$\frac{dQ_f}{dE_i} = 1 - \frac{d}{dE_i}\left(\sum_i Y_i m(A_i, Z_i)\right) - m_n \frac{d\bar{\nu}_T}{dE_i}. \tag{44}$$

Using the information given in Table 16, values of dQ_f/dE_i have been calculated for the various nuclides and are listed in Table 21. The agreement between dQ_f/dE_i values obtained by the two methods is reasonably good considering the available data.

8. SUMMARY

In this work, the total energy released in the fission process has been calculated for a number of the more common fissile and fertile materials. Also as a part of this work, the individual contributions to the total energy release have been assessed. Such evaluations are difficult to perform because of the nonexistence of necessary data or in many cases because of the poor quality of the existing data. This is rather unfortunate, since precision measurements can now be made with existing experimental methods. However, there appears to be no large concerted effort or interest on the part of funding agencies or research establishments for such measurements. Because of the lack of accurate data for the energies of individual contributions to the total energy release, the mass-excess calculational procedure described in Sects. 1 and 2 was used in this work to determine the total energy release in fission. This approach was found to be quite satisfactory and gave accurate values for the total energy release, as was concluded also by Walker[2] and James.[3] Because of the constancy of the average mass excesses of the fission products, this calculational procedure can be used quite accurately to estimate the total energy release for those fissioning systems in which only the target nuclide mass excess and the average number of neutrons emitted ($\bar{\nu}_T$) are known.

Although the total energy release in fission can be calculated accurately, great difficulties exist in the accurate determination of the individual contributions. The major difficulties are present in the determination of the total fragment kinetic energies $\bar{E}_K$, the beta-particle energies $\bar{E}_\beta$, the antineutrino energies $\bar{E}_{\bar{\nu}}$, and to a lesser extent the gamma-ray energies.

It was shown in Sect. 3.1 that a discrepancy of 4.1 MeV exists between the total fragment kinetic energies measured using two different experimental

methods. More precise double-velocity measurements, based on absolute calibrations, are clearly needed to resolve this discrepancy.

Beta-particle energy data exist only for thermal-neutron-induced fission of ^{235}U; and, as can be seen in Table 9, rather poor agreement exists between the eight measurements performed during a time span of 11 years. Since no beta-particle energy data exist for other fissioning systems, these values can only be estimated. In this study, this estimate was calculated using the value for ^{235}U and the relative squares of the calculated beta-decay chain lengths as discussed in Sect. 3.4 and Appendix A. There are no independent estimates of the antineutrino energies, and they must be calculated from the assumed beta-particle energies. In this work, the beta-particle and antineutrino energies (a total of ~22 MeV) for all fissioning systems are based entirely on the poorly known total beta-particle energy for ^{235}U. To obtain better estimates of the total energy release by summation of the individual contributions, more accurate total beta-particle energy measurements must be made and extended to other fissioning systems. Also, to calculate the heat produced in a reactor using the more precise mass-excess calculations, the estimation of antineutrino energies determines the ultimate accuracy of the results. Again, more precise beta-particle energy measurements would improve the accuracy of these latter calculations.

Finally, note that not all fission cross sections and $\overline{\nu}_T$ values (primarily those of ^{242}Pu) are well known as a function of incident neutron energy. The mass-yield distributions of all nuclides are generally known only at two or three values of E_i, if they are known at all. One of these E_i values is commonly described as "fission-spectrum" neutrons. This term is rather ill-defined since it often involves neutrons in a specific reactor whose neutron-energy spectrum depends on the loading of the reactor. The term may even apply to neutrons emitted in the fission of different nuclides, e.g., ^{235}U or ^{238}U. Measurements of the fission-product mass yields for the various nuclides at discrete values of E_i would permit the calculation of Q_f for any type of neutron spectrum.

APPENDIX A

Total Beta-decay Chain Lengths

Several methods can be used to compute average beta-decay chain lengths. We have chosen a method that computes beta-decay chain lengths relative to ^{235}U and uses the empirical observations that: (1) The difference, Δ, between the average charge of a fragment formed directly in fission, $Z_p(A_i)$, and that expected on the basis of the "Unchanged Charge Density" assumption, $(Z_F/A_F)A_i$ (the charge density of the preneutron emission fragment is the same as that of the fissioning nucleus), is approximately constant for low-energy fission;[23] i.e.,

$$\overline{Z}_p(A_i) - \frac{Z_F}{A_F}A_i = \text{constant} = \Delta. \tag{45}$$

The Δ values for light mass fragments have been found[23] to be approximately +0.5 charge unit, and the complementary heavy fragments have Δ values of approximately -0.5. (2) An approximate universal neutron function exists for low-energy fission;[39] i.e., for low-energy fission, a fragment with initial mass A_i emits approximately the same number of neutrons, independent of the fissioning system, to form the final mass A_f. The average beta-decay chain length for one fragment with final mass A_f is given as

$$\overline{N}_\beta(A_f) = Z_s(A_f) - \overline{Z}_p(A_i) = Z_s(A_f) - \left(\frac{Z_F}{A_F}A_i + \Delta\right), \tag{46}$$

where $Z_s(A_F)$ is the charge of the first stable mass along a beta-decay chain. The beta-decay chain length for a fragment formed from a given fissioning system relative to the same fragment formed in thermal fission of ^{235}U is

$$\Delta N_\beta(A_f) = \overline{N}_\beta(A_f) - \overline{N}_\beta(A_f, {}^{235}U) \tag{47}$$

$$\simeq A_i\left(\frac{92}{236} - \frac{Z_F}{A_F}\right). \tag{48}$$

Summing together the beta-decay chain lengths of both complementary fragments, one obtains an estimate for the total beta-decay chain length per fission relative to ^{235}U,

$$\Delta\overline{N}_{\beta T} \simeq A_F\left(\frac{92}{236} - \frac{Z_F}{A_F}\right), \tag{49}$$

where Z_F and A_F are the charge and mass number of the fissioning nucleus.

The computed $\Delta\overline{N}_{\beta T}$ values are given in Table 22. Using the experimentally determined value of 5.98 for ^{235}U, the values for other fissioning systems were calculated using Eq. 47. In Table 22, these calculated values are compared with the measured values of Seyfarth et al.[80] and also with the values obtained from the mass-yield distributions (see Sect. 2). In general, the agreement between the various values is quite good.

TABLE 22. Beta-decay Chain Lengths

Target	$\Delta\overline{N}_{\beta T}$	$\overline{N}_{\beta T}$ (Seyfarth[80])	$\overline{N}_{\beta T}$ (calculated)	$\overline{N}_{\beta T}$ (mass yield)
^{232}Th	0.830		6.81	7.29
^{233}U	-0.780	5.33 ± 0.2	5.20	5.15
^{235}U	0	5.98 ± 0.2	5.98 (norm)	6.14
^{238}U	+1.169		7.15	6.73
^{239}Pu	-0.441	5.57 ± 0.2	5.54	5.50
^{240}Pu	-0.051		5.93	
^{241}Pu	+0.339		6.32	6.25
^{242}Pu	+0.729		6.71	

We have attempted to demonstrate that the $\overline{E}_{\gamma d}$ values are approximately proportional to $\overline{N}^2_{\beta T}$, as discussed in Sects. 3.3.3 and 3.4. Table 23 compares the delayed gamma-ray energies from Table 8 relative to ^{235}U with the $\overline{N}^2_{\beta T}$ values relative to ^{235}U. In general, the agreement is good, indicating that $\overline{E}_{\gamma d} \simeq \overline{N}^2_{\beta T}$.

TABLE 23. Comparison of Delayed Gamma-ray Energies to $\overline{N}^2_{\beta T}$

Target	$\left[\frac{\overline{N}_{\beta T}}{\overline{N}_{\beta T}(^{235}U)}\right]^2$	$\frac{\overline{E}_{\gamma d}}{\overline{E}_{\gamma d}(^{235}U)}$ [a]
^{232}Th	1.30	1.27 ± 0.31
^{233}U	0.76	0.83 ± 0.24
^{235}U	1	1
^{238}U	1.43	1.27 ± 0.31
^{239}Pu	0.86	0.96 ± 0.28

[a] $\overline{E}_{\gamma d}$ from Table 8.

APPENDIX B

Energy Release Resulting from Neutron-capture (n,γ) Reactions

The energy released by capture of neutrons in reactor materials can be calculated if a detailed-neutron balance exists for the reactor, indicating quantitatively the number of neutrons captured by various materials. As an illustration, the energy released by neutron capture throughout the core and blanket of a ^{235}U-fueled EBR-II type reactor is calculated. The energy-release calculation includes the Q value of the initial (n,γ) reaction and the energy released in subsequent beta- and gamma-ray decays (omitting anti-neutrino energies) of radioactive species with half-lives less than 10 years. The mass tables of Mattauch et al.,[10] were used for the Q values, the decay schemes were taken from the compilation of Lederer et al.,[96] and the average beta-particle energies were calculated from the total beta-decay energies assuming allowed beta shapes and using the tables of Widman et al.[80] The required data as well as the results of this calculation are given in Table 24. The results of this calculation show that an average energy release of 6.53 MeV is expected per neutron capture for this type of reactor.

TABLE 24. Energy Release by Neutron Capture for a ^{235}U-fueled EBR-II Assembly

Target		% Isotopic Abundance	$Q_{nc}(n,\gamma)$	Assumed % Composition	Relative Capture Cross Section (thermal)	Neutron Inventory % Total (n,γ)
^{235}U			6.47			16.1
^{238}U			5.67			57.0
Stainless Steel	^{54}Fe	5.84	9.31	68	2.9	25.4
	^{56}Fe	91.66	7.64		2.7	
	^{57}Fe	2.17	10.04		2.5	
	^{58}Fe	0.31	7.88		1.1	
	^{50}Cr	4.31	9.30	19	17	
	^{52}Cr	83.76	7.94		0.8	
	^{53}Cr	9.55	9.72		18	
	^{54}Cr	2.38	7.35		0.38	
	^{58}Ni	67.76	9.00	10	4.4	
	^{60}Ni	26.16	7.82		2.6	
	^{61}Ni	1.25	10.60		2	
	^{62}Ni	3.66	6.84		15	
	^{64}Ni	1.16	7.26		1.5	
	^{55}Mn		9.89	2	13.3	
	^{28}Si	92.18	8.48	1	0.08	
	^{29}Si	4.71	10.62		0.3	
	^{30}Si	3.12	7.18		0.11	
^{22}Na			11.64			1.5
^{16}O			4.14			0.06

Total average energy release Q_{nc} = 6.53 MeV/capture.
Estimated error = ±0.2 MeV.

The calculation of the energy release for stainless steel required several assumptions. The neutron inventory cited only that fraction of

neutrons captured by stainless steel and not by the individual nuclides present. Therefore, to perform an exact calculation, it would be necessary to know the appropriate neutron spectrum for the stainless steel as well as the energy-dependent neutron-capture cross section for the various isotopes. These data were not available, and we have assumed that the individual isotopic contributions to the energy release are simply proportional to the thermal-neutron capture cross sections. Making a more drastic assumption that all the total capture cross sections are equal results in a change of the total energy release per capture for this reactor configuration from 6.53 to 6.48 MeV, a negligible difference.

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