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A REVIEW OF U-235 DECAY HEAT MEASUREMENTS AND CALCULATIONS

Mesures et calculs relatifs à la chaleur de désintégration de U-235

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Chalk River, Ontario

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Résumé

On analyse les récentes mesures obtenues par scintillateur de la puissance β et γ de désintégration des produits de fission ainsi que les mesures calorimétriques de leur somme afin d'obtenir une estimation de E_β et E_γ, composants β et γ de l'énergie retardée par fission dans un réacteur. Des calculs fondés sur la bibliothèque des constantes ENDF/B-4 des produits de fission sont comparés aux résultats mesurés et employés pour estimer les contributions à E_β et E_γ pour les temps de désintégration supérieurs à 10^5 s. Une valeur de E_ν, composant antineutrino, compatible avec le composant mesuré est également calculée.

On constate que la chaleur de désintégration mesurée dans deux expériences calorimétriques (somme des composants β et γ) est environ 15% plus élevée que les énergies mesurées séparément (moyennes des mesures 5β et 2γ). Ainsi, E_β et E_γ peuvent varier énormément selon la normalisation. Après avoir considéré toutes les incertitudes expérimentales, la gamme des valeurs possibles a comme limites inférieures les valeurs calculées à l'aide du fichier ENDF/B-4, ses limites supérieures étant environ 40% plus élevées.

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ABSTRACT

Recent scintillator measurements of fission product decay β and γ power, and calorimetric measurements of their sum are analyzed to obtain estimates of E_β and E_γ, the β and γ components of the delayed energy per fission in a reactor. Calculations using the ENDF/B-4 fission product file are compared to the measured results and used to estimate the contributions to E_β and E_γ for decay times greater than 10^5s. A value of E_ν, the anti-neutrino component, consistent with the measured component is also calculated.

It is found that the decay heat measured in 2 calorimetric experiments (the sum of the β and γ components) is about 15% greater than the separately measured energies (averages of 5 β and 2 γ measurements). Thus, depending on normalization, E_β and E_γ can vary widely. After all experimental uncertainties are taken into account the range of possible values have, as lower limits, the values calculated using ENDF/B-4, with upper limits about 40% greater.

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INTRODUCTION

Energy per Fission

The total decay energy, Q, can be calculated by mass balance if chain yields and mass decrements are known (Walker, 1978; James, 1969; Unik and Gindler, 1971; Sher and Beck, 1979). Values of Q are quite insensitive to uncertainties in these data and are known to a few hundreds of keV for the more important fissile nuclides.

The total decay energy appearing as heat in a reactor is given by

$$H=Q-E_{\nu}=Q_{prompt}+Q_{delayed}-E_{\nu}.$$

where E_{ν}, the average kinetic energy of the anti-neutrinos accompanying β-decay, has an uncertainty of at least 1 MeV. Q_{prompt} is the sum of the kinetic energies of the fission fragments and prompt neutrons and the photon energy of the prompt γ rays, while $Q_{delayed}$ is the delayed portion of Q due to β-decay, with components E_{β}, E_{γ}, E_{ν} and E_{nd} due to the betas, gammas, anti-neutrinos and delayed neutrons respectively. The delayed neutron component is a small term, appreciably less than 100 keV.

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The delayed components E_β, E_γ and E_ν are of interest, the first 2 as the source of afterheat in a loss-of-coolant accident and E_ν because of its importance in determining total fission heating, H.

E_β, E_γ and E_ν can also be calculated from detailed nuclide data contained in fission product files such as the one in ENDF/B-4. The file contains a complete set of direct yields as well as values, for every radioactive fission product of q_β, the total decay energy, and e_β and e_γ, the average β and γ-decay energies. If details of the radioactive decay are available e_β and e_γ are based on transition probabilities and, for e_β, on the known or assumed β spectrum. For other nuclides they are based on semi-empirical calculations. Values of e_β, e_γ and the direct yields have been incorporated into the FISSPROD-2 data library (Walker,1975), and this program has been used to obtain the calculated β and γ-decay powers given in this report.

Comparison of Measurements

Earlier β and γ power measurements were evaluated by Perry et al (1973). Their approach has been followed closely here, and applied to several recent measurements in addition to 2 of the β power measurements included in their evaluation.

Let $f_x(t)$ be the decay power, in MeV/fission second, at a time t after a fission pulse. Here x can be β, γ or ν. In terms of individual fission products, as discussed in the preceding section,

$$f_x(t) = \sum_{j=1}^{N} e_{xj} \; dn_j(t)/dt$$

where n_j is the number of atoms of the j^{th} fission product and N is the total number of fission products.

For an irradiation of duration T at a constant fission rate, the decay heat t seconds after the end of the irradiation is given by

$$F_X(T,t) = \int_0^T f_X(t+\tau)d\tau$$

where $F_X(T,t)$ has units of MeV/s÷fissions/s

The experiments considered here measured $F_X(T,t)$ for a wide variety of irradiation and decay times, and therefore cannot be compared directly. A quantity that can be compared directly is the integral of $f_X(t)$ over a range of time intervals compatible with the measured decay times, i.e.

$$\Delta E_{Xi} = \int_{t_i-1}^{t_i} f_X(\tau)d\tau$$

An approximation to the instantaneous fission decay power, $f_X(t)$, can be derived from each experimental set of $F_X(T,t)$ by numerical methods with respect to T. A computer program supplied by R.E. Schenter of Hanford Engineering Development Laboratory was used (Schmittroth and Schenter, 1979). It is assumed that $f_X(t)$ can be represented by $\sum_i \alpha_i \exp(-\lambda_i t)$ Values of λ_i are input parameters and the program calculates the corresponding α_i's.

EXPERIMENTAL RESULTS

The sources of data, the measurement technique, and irradiation decay time ranges are summarized in Table 1.

The β results of Armbruster and Meister (1962) and Tsoulfanidis et al (1971) were not used. In the former experiment fission fragments were separated by an on-line mass separator so that decay rate and decay power were determined for light and heavy fragments separately. A comparison with calculated values based on ENDF/B-4 shows that while the ratio of light to heavy β-decay is reasonable the ratio of light to heavy decay energy is not. Their experiment gives 2.0 for the latter while ENDF/B-4 predicts 1.3. Although the ENDF/B-4 fission product file does have shortcomings they are not expected to result in a discrepancy of this magnitude.

Results from the second experiment are too few - 7 points from 0 to 10^5 s decay - to give meaningful integrals over the short decay intervals used here (3 per decade). Their results are 15-20% higher than the average of the experiments listed in Table 1.

β-radiation

Table 2 compares 5 sets of β-decay power measurements. The results from each laboratory have been averaged if there is more than 1 set, i.e. 2 or more different irradiation times. The uncertainty, when listed, is the standard deviation from the average.

Where divergence is unusually large, some data has been omitted. For $t_i > 10^4$ s the $T=10^5$ s results of McNair et al (1969) are about 50% greater than those for $T=10^4$ s, and are not included. In the results of MacMahon et al (1970), for the same decay time range, the $T=10^4$ s data averages about 25% less than the $T=10^3$ s results and have been omitted. The omissions do not change the overall averages appreciably, but reduce the scatter to values typical of results at shorter decay periods.

Four of the sets listed in Table 2 have the decay period 5-10^4 s in common (i=4 to 13). The sums $\sum_{i=4}^{13} \Delta E_{\beta i}$ have been averaged and each set has then been renormalized to this average (3.91±0.237 MeV/fission). The largest renormalizations are a 7% reduction in the results of Friesenhahn et al (1976) and an 8% increase in the results of MacMahon et al (1970). The latter increase also applies to the results of Alam and Scobie (1974).

The renormalized $\Delta E_{\beta i}$ are listed in Table 3 along with their average values. In the process of averaging only 1 value was rejected - that of Friesenhahn et al for the period 0-1 s. Not only is the value very small, but the β power actually increased in this interval, from 0.553 MeV/fission at 0.75 s to 0.559 at 1.0 s. While there is no measured data that is directly comparable, calculations based on ENDF/B-IV predict a decrease of 6½%.

For the next time interval, 1-2 s, the three measurement again give discrepant results, but here no two agree, being approximately in the ratio $1:1.5:(1.5)^2$. The mean has a standard deviation of 43%. It is encouraging that over the decay time range 0-5 s the averages agree quite well with the results of Alam and Scobie, since their experiment is the only one designed primarily to measure decay power in this interval.

γ-radiation

The earlier results evaluated by Perry et al (1973) showed large discrepancies and were not included here. The 2 recent measurements that are included are associated with 2 of the β-measurements (Friesenhahn et al, 1976; Dickens et al, 1977). These are listed in Table 3 as the ratio $\Delta E_{\gamma i}/\Delta E_{\beta i}$ and the average ratios are then multiplied by the average $\Delta E_{\beta i}$ to obtain the values of $\Delta E_{\gamma i}$ in the last column.

For the first two intervals the measured ratios are not used. The results of Friesenhahn et al (1976) give ratios that are much larger than those for longer decay times. Since calculated ratios based on ENDF/B-4 agree with measured ratios for $i>2$ and show little change for $i=1$ or $i=2$, they have been used in place of the measured ratios.

Differences between the two sets of ratios are compatible with measured uncertainties except between 2000 s and 10^4 s ($i=11,12$). About half the differences here are due to differences in $\Delta E_{\beta i}$ and these appear to be associated with rapid variations in the β-power measured by Friesenhahn et al relative to calculated values.

Calorimetric Measurements

Results from the analysis of two sets of calorimetric measurements are given in Table 4 (Lott et al, 1973; Yarnell and Bendt, 1977). In the latter experiment a liquid He bath was used to minimize the calorimeter response time, so that measurements were able to start 10 s after the end of the irradiation. The two calorimetric measurements agree for cooling times greater than 500 s ($i\geq10$).

Table 4 also includes the sums $\Delta E_{\beta i}+\Delta E_{\gamma i}$ using the averages from Table 3, and calculated values based on ENDF/B-4. The same information is presented graphically in Fig. 1, except that the continuous variable $t(f_\beta(t) + f_\gamma(t))$ has been used instead of histograms of $\Delta E_{\beta i} + \Delta E_{\gamma i}$.

From a comparison of the 3 results it can be seen that major divergences occur for times less than 10-20 s, with decay heat calculated from ENDF/B-4 much smaller than either of the measured quantities. From 50 s to 1000 s the calculated decay heat agrees with the sum of the separately measured β and γ components, and agrees with the calorimetric measurements for time greater than 2000 s. For $t>50$ s the sum of the separately measured components average about 15% less than calorimetric measurements.

DISCUSSION

For decay periods longer than $\sim$1000 s after a fission burst all nuclides making a significant contribution to decay heat will be displaced only 1 or 2 decays from the stable end products of their decay chains. Since the decay products of these nuclides have been measured, with only a few exceptions, the calculated decay power should be accurate in this time range. Schmittroth and Schenter (1977) estimate an uncertainty of $\sim$5% for U-235 at 200 s cooling, decreasing at longer times to $\sim$3% at 10^5 s.

In view of the good agreement between calculated and calorimetric decay heat above 1000 s it is tempting to assume the calculated components really are known accurately and, therefore, that the measured $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$ should be renormalized to agree with calculation in this time range. The corollary would be that calculated components are too small for shorter decay periods due to inaccurate data.

For the time range 1000 s to 10^5 s the required normalizations are 1.061 and 1.196 for $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$ respectively. While the β renormalization is within the uncertainty in the original averaging procedure, a 13% change in $\Delta E_{\gamma i}/\Delta E_{\beta i}$ appears to be in complete disagreement with the measured ratios.

Immediately following completion of the ENDF/B-4 fission product file a concerted effort was made to detect data errors by comparing calculated and measured decay heat. These comparisons resulted in the identification of several nuclides for which the ENDF/B-4 decay data had been entered incorrectly (Schmittroth and Schenter, 1977). These errors included incorrect half-lives, resulting in the transfer of a particular decay energy to the wrong time range, and incorrect decay energies which distorted the relative β to γ-decay power over several time intervals. These incorrect data have been corrected in the ENDF/B-4 fission product file and in the FISSPROD-2 library. It is unlikely, therefore, that "clerical" errors with effects of this magnitude still exist in ENDF/B-4. However, it is quite possible that some of the "known" data was measured incorrectly and that new measurements would result in significant changes in calculated decay heat.

The discrepancies between individual β and γ measurements, calorimetric measurements and calculated decay power increase the uncertainties in the decay components E_β, E_γ and E_ν. To obtain a better idea of the magnitude of these uncertainties the consequences of 3 assumptions and their requisite normalizations are compared.

Assumption 1. The β and γ measurements do not include any systematic errors or other bias and the values listed in Table 3 are correct within the stated uncertainties.

Assumption 2. The calorimetric measurements are the best measure of total (β+γ) heat, and the separate β and γ energies of Table 3 should be normalized to them over the time interval 1000 to 10^5 s. The normalization factor is 1.148 .

Assumption 3. The ENDF/B-4 calculations are the best measure of component energies in the time interval 1000 to 10^5 s. This requires that average $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$ values of Table 3 should be multiplied by 1.061 and 1.196 respectively.

Table 5 summarizes the results of these assumptions in terms of the total β, γ and anti-neutrino decay energies. The latter cannot be calculated directly using FISSPROD-2 (Walker 1975) since q_ν values are not available in the program's data library. Instead, an approximation was made by assuming a linear variation of e_ν/e_β with ln e_β, with the slope depending on mass range and the magnitude of e_β (greater or less than 1.5

MeV). The resultant $\Delta E_{\nu i}$ (approx.) were normalized so that their sum, to infinite decay time, agreed with the value obtained with ENDF/B-4 data by other methods (Walker 1976). The calculated ratios $\Delta E_{\nu i}/\Delta E_{\beta i}$ were then used with the $\Delta E_{\beta i}$ of Table 3.

When the uncertainties in the original β normalization (6%) and in the individual $\Delta E_{\beta i}$ are taken into account the three delayed components have a high probability of lying within the following ranges:

E_β - 6.5 to 8.9 MeV/fission
E_γ - 6.0 to 8.7 MeV/fission
E_ν - 8.6 to 12.0 MeV/fission

Table 6 compares $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$ using Assumption 3 with the results of Perry et al (1973) and calculated values, and their sum with the average calorimetric results. The choice of Assumption 3 values does not indicate that this data is preferred, but simply that it is easier to compare data in a table when they are similar over part of their range.

For β radiation, agreement is generally good from 100s to 10^5s between all 3 sets. The Perry et al (1973) $\Delta E_{\beta i}$ for i=2 and 3 are appreciably larger than those from the current evaluation reflecting the relatively larger $\Delta E_{\beta i}$ of McNair et al (1969) compared to those derived from later results (Alam and Scobie, 1974; Friesenhahn et al, 1976).

Over most of the time intervals the $\Delta E_{\gamma i}$ values of Perry et al (1976) are appreciably greater than assumption 3 values, even though these have already been increased nearly 20% over the initial estimate in Table 3. After 100 s they average 13±3% greater.

The sums of measured $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$, renormalized using Assumption 3, are in very good agreement with the average calorimetric values except for i=5. Calculated $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$ sum to totals that are about 5% lower than calorimetric up to i=12 (2000 s) and agree for longer decay times.

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To summarize, 5 β, 2 γ and 3 total decay power measurements have been compared using partial decay energies.

Values of $\Delta E_{\beta i}$ differed mainly in their normalization, with a range of 15% between the highest and lowest measurements. When renormalized to a median value they were in substantial agreement except in the decay interval 0-5 s. These 3 intervals, covering the period 0-5 s are the source of most of the uncertainty in the value of E_β obtained by summing from 0 to 10^5 s.

The two measurements of γ power were done in conjunction with two β power measurements. Ratios of $\Delta E_{\beta i}/\Delta E_{\gamma i}$ agree quite well from 2 to 10^4 s cooling time. In the period 0-2 s, covered, by only 1 experiment, the measured ratios appear anomolously high and calculated ratios were substituted.

The sums, $\Delta E_{\beta i} + \Delta E_{\gamma i}$, from experiment are about 15% smaller than calorimetric measurements for decay times greater than 20 s.

Values of $\Delta E_{\beta i}$ and $\Delta E_{\gamma i}$ calculated using the ENDF/B-4 fission product file do not fit any of the experiments well for decay times less than about 1000 s.

When all these discrepancies are taken into account it is concluded that the components of $Q_{delayed}$, the delayed energy per fission, have values in a range which has, as lower limit, the components based on ENDF/B-4 and an upper limit some 40% greater. Consequently the total heat released in a reactor per U-235 fission, H, is uncertain by about 3.5 MeV due to the uncertainty in E_ν, the energy carried away by anti-neutrinos.

The higher $Q_{delayed}$ values, i.e. those that agree with either the calorimetric or summed β and γ results, imply a Q_{prompt} that is consistent with the values of fission fragment energy measured calorimetrically or by time-of-flight rather than the larger values measured by surface barrier detectors. On the other hand the value of $Q_{delayed}$ based on ENDF/B-4 gives a value of Q_{prompt} consistent with the surface barrier detector measurements. (Walker, 1976, p.14).

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TABLE 1

DATA SOURCES FOR DECAY POWER

Reference	Method	Radiation Measured	Irradiation Time T(s)	Decay Time Ranges(s)	No. of Data Points
McNair et al (1969)	Scintillator	β	10	7-900	60
			100	7-5000	80
			1000	$7\text{-}1.4\times10^4$	90
			10^4	$7\text{-}9.9\times10^4$	118
			10^5	$7\text{-}5.0\times10^5$	148
MacMahon et al (1970)	Scintillator	β	10	$10\text{-}1.5\times10^4$	21
			100	$4\text{-}3.0\times10^4$	30
			1000	$35\text{-}10^5$	34
			10^4	$35\text{-}10^5$	34
Alam and Scobie (1974)	Scintillator	β^a	10	0.3-26.2	58
			100	0.3-26.2	58
Friesenhahn et al (1976)	Nuclear Calorimeter	$\beta+\gamma$, γ^b	24 hr	$0.75\text{-}1.5\times10^5$	86
Dickens et al (1977)	Scintillator	β,γ	1	1.7-90	14
			10	10.7-795	14
			100	70-395	14
Lott et al	Calorimeter	$\beta+\gamma$	100	70-3000	11
			1000	$20\text{-}2\times10^4$	13
			5000	$300\text{-}7\times10^4$	15
Yarnell and Bendt (1977)	Calorimeter	$\beta+\gamma$	2×10^4	$10\text{-}10^5$	23

a relative values normalized to data of MacMahon et al (1970)

b β components obtained as difference

TABLE 2

EXPERIMENTAL β DECAY ENERGY

$$\Delta E_{\beta i} = \int_{t_{i-1}}^{t_i} f_\beta(\tau)d\tau \text{ (MeV/fission)}$$

i	t_i	McNair(1969)	MacMahon('70)	Alam(1974)	Friesenhahn('76)	Dickens(1977)
1	1	1.196±.181		1.213±.291	0.2465	
2	2	0.596±.043		0.352±.072	0.271	
3	5	0.779±.011		0.617±.079	0.641	0.6195
4	10	0.590±.007	0.560±.016	0.532±.053	0.598	0.549
5	20	0.552±.007	0.499±.021	0.5115±.024	0.564	0.523±.002
6	50	0.607±.003	0.583±.005		0.634	0.607±.001
7	100	0.3945±.0012	0.389±.006		0.448	0.4075±.0065
8	200	0.343±.002	0.329±.009		0.382	0.366±0.018
9	500	0.383±.005	0.357±.001		0.419	0.407±.012
10	1000	0.278±.0035	0.2555±.006		0.3415	0.3035±.0085
11	2000	0.271±.003	0.251±.003		0.297	0.307
12	5000	0.295±.006	0.260±.006		0.317	0.335
13	10000	0.161±.019	0.137±.004		0.187	0.182
14	20000	0.149	.118		0.1545	
15	50000	0.184	.147		0.187	
16	10^5	0.105	.0905		0.106	
17	$2x10^5$				0.067	
$\sum_{i=4}^{13}\Delta E_{\beta i}$		3.875	3.620		5.188	3.987

TABLE 3

NORMALIZED β AND γ DECAY ENERGY

$$\Delta E_{xi} = F \cdot \int_{t_{i-1}}^{t_i} f_x(\tau)d\tau \text{ (MeV/fission)}$$

		$\Delta E_{\beta i}$						$\Delta E_{\gamma i}/\Delta E_{\beta i}$			
i	t_i	McNair	MacMahon	Alam	Friesenhahn	Dickens	Average	Friesenhahn	Dickens	Average	$\Delta E_{\gamma i}$
	F =	1.011	1.082	1.082	0.9354	0.9825	-	-	-	-	-
1	1	1.210	-	1.312	0.231^x	-	1.261±.360	1.681		(.75)*	(0.95)
2	2	0.602	-	0.381	0.253	-	0.412±.177	1.053		(.73)*	(0.30)
3	5	0.787	-	0.668	0.600	0.609	0.666±.086	0.787	0.729	0.758±.041	0.505
4	10	0.597	0.606	0.576	0.560	0.539	0.575±.027	0.698	0.726	0.712±.020	0.409
5	20	0.558	0.540	0.5535	0.5275	0.514	0.539±.018	0.781	0.792	0.786±.008	0.423
6	50	0.614	0.631		0.593	0.597	0.609±.018	1.005	1.000	1.002±.003	0.610
7	100	0.399	0.421		0.419	0.400	0.410±.012	1.052	1.178	1.115±.089	0.457
8	200	0.3465	0.356		0.358	0.360	0.355±.006	1.131	1.125	1.128±.004	0.400
9	500	0.387	0.387		0.392	0.400	0.392±.006	1.133	1.085	1.109±.034	0.435
10	1000	0.281	0.2765		0.319	0.298	0.294±.019	0.991	1.003	0.997±.008	0.293
11	2000	0.274	0.272		0.278	0.301	0.281±.014	1.161	0.977	1.069±.130	0.300
12	5000	0.298	0.281		0.296	0.329	0.301±.020	1.316	1.116	1.216±.143	0.366
13	10^4	0.163	0.148		0.1745	0.179	0.166±.014	1.326	1.391	1.358±.046	0.225
14	2×10^4	0.150	0.128		0.1445		0.141±.012	1.209		1.209	0.170
15	5×10^4	0.186	0.159		0.175		0.173±.014	0.874		0.874	0.151
16	10^5	0.106	0.098		0.99		0.101±.005	0.870		0.870	0.088
17					0.63		0.063	1.091		1.091	0.069

* Calculated ratios using ENDF/B-4 data. See text.

^{x} not used in taking average

TABLE 4

TOTAL DECAY HEAT

		calorimetric*		$\Delta E_{\beta i}+\Delta E_{\gamma i}$*	
i	t_i	Lott(1973)	Yarnell(1977)	Averages (Table 3)	ENDF/B-4
1	1	-	-	2.211	1.007
2	2	-	-	0.712	0.535
3	5	-	-	1.171	0.951
4	10	-	-	0.984	0.892
5	20	-	1.267	0.962	1.000
6	50	-	1.385	1.219	1.309
7	100	-	0.973	0.867	0.915
8	200	0.761	0.837	0.755	0.741
9	500	0.876	0.941	0.827	0.858
10	1000	0.650	0.658	0.587	0.607
11	2000	0.661	0.664	0.581	0.624
12	5000	0.765	0.766	0.667	0.752
13	10^4	0.462	0.455	0.391	0.469
14	2×10^4	0.360	0.368	0.311	0.358
15	5×10^4	0.368	0.371	0.324	0.378
16	10^5	0.204	0.210	0.189	0.208
17	2×10^5			0.132	0.141
$\sum_{i=11}^{16} \Delta E_{(\beta+\gamma)i}$		2.820	2.834	2.463	2.789

* MeV/fission

TABLE 5

TOTAL β,γ AND ν^- DECAY ENERGIES

	E_β[a]	E_γ[b]	E_ν[c]	$Q_{delayed}$[d]
	MeV/fission			
Assumption 1	7.106	6.696	9.47	23.28
Assumption 2	8.199	7.726	10.93	26.86
Assumption 3	7.539	8.008	10.05	25.61
ENDF/B-4[e]	6.435	6.281	8.65	21.38

a Including 0.430 MeV/fission for the interval 10^5s to infinite decay time, calculated using ENDF/B-4 decay data.

b Including 0.682 MeV/fission for the interval 10^5s to infinite decay time, calculated using ENDF/B-4 decay data.

c Including 0.73 MeV/fission for the interval 10^5s to infinite decay time, assuming $\Delta E_\nu/\Delta E_\beta=1.7$ in this interval.

d $Q_{delayed} = E_\beta+E_\gamma+E_\nu+0.0074$ (delayed neutron energy).

e From Walker, 1976.

TABLE 6

COMPARISON OF MEASURED $\Delta E_{\beta i}$ AND $\Delta E_{\gamma i}$ WITH CALCULATED AND CALORIMETRIC VALUES

		$\Delta E_{\beta i}$(MeV/fiss)			$\Delta E_{\gamma i}$(MeV/fiss)			"Total" Decay Heat		
i	t_i(s)	Meas[a]	Perry et al(1973)	Calc[c]	Meas[b]	Perry et al(1973)	Calc[c]	Average Calorimetric	$\Delta E_{\beta i}+\Delta E_{\gamma i}$	
									Meas	Calc
1	1	1.338		0.577	1.136		0.430		2.47	1.01
2	2	0.437	0.614	0.310	0.359	0.327	0.225		0.80	0.54
3	5	0.706	0.819	0.556	0.603	0.589	0.395		1.31	0.95
4	10	0.610	0.626	0.522	0.489	0.499	0.370		1.10	0.89
5	20	0.572	0.581	0.571	0.506	0.524	0.429	1.27	1.08	1.00
6	50	0.646	0.660	0.700	0.730	0.737	0.609	1.39	1.38	1.31
7	100	0.435	0.428	0.462	0.547	0.576	0.453	0.97	0.98	0.92
8	200	0.377	0.367	0.352	0.478	0.532	0.389	0.84[d]	0.85	0.74
9	500	0.416	0.416	0.425	0.520	0.593	0.433	0.91	0.94	0.86
10	1000	0.312	0.292	0.297	0.350	0.401	0.310	0.65	0.66	0.61
11	2000	0.298	0.284	0.288	0.359	0.396	0.336	0.66	0.66	0.62
12	5000	0.319	0.314	0.309	0.438	0.482	0.443	0.76	0.76	0.75
13	10^4	0.176	0.164	0.183	0.269	0.300	0.286	0.46	0.45	0.47
14	2×10^4	0.150	0.145	0.155	0.203	0.232	0.203	0.36	0.35	0.36
15	5×10^4	0.184	0.178	0.194	0.180	0.207	0.184	0.37	0.36	0.38
16	10^5	0.107	0.104	0.105	0.105	0.123	0.103	0.21	0.21	0.21
17	2×10^5	0.067	0.068	0.062	0.082	0.102	0.079		0.15	0.14

a From Table 3, renormalized as in Assumption 3(x1.061)

b From Table 3, renormalized as in Assumption 3(x1.196)

c Calculated with FISSPROD-2 using the ENDF/B-4 fission product file

d Using the value of Yarnell and Bendt (1977) only

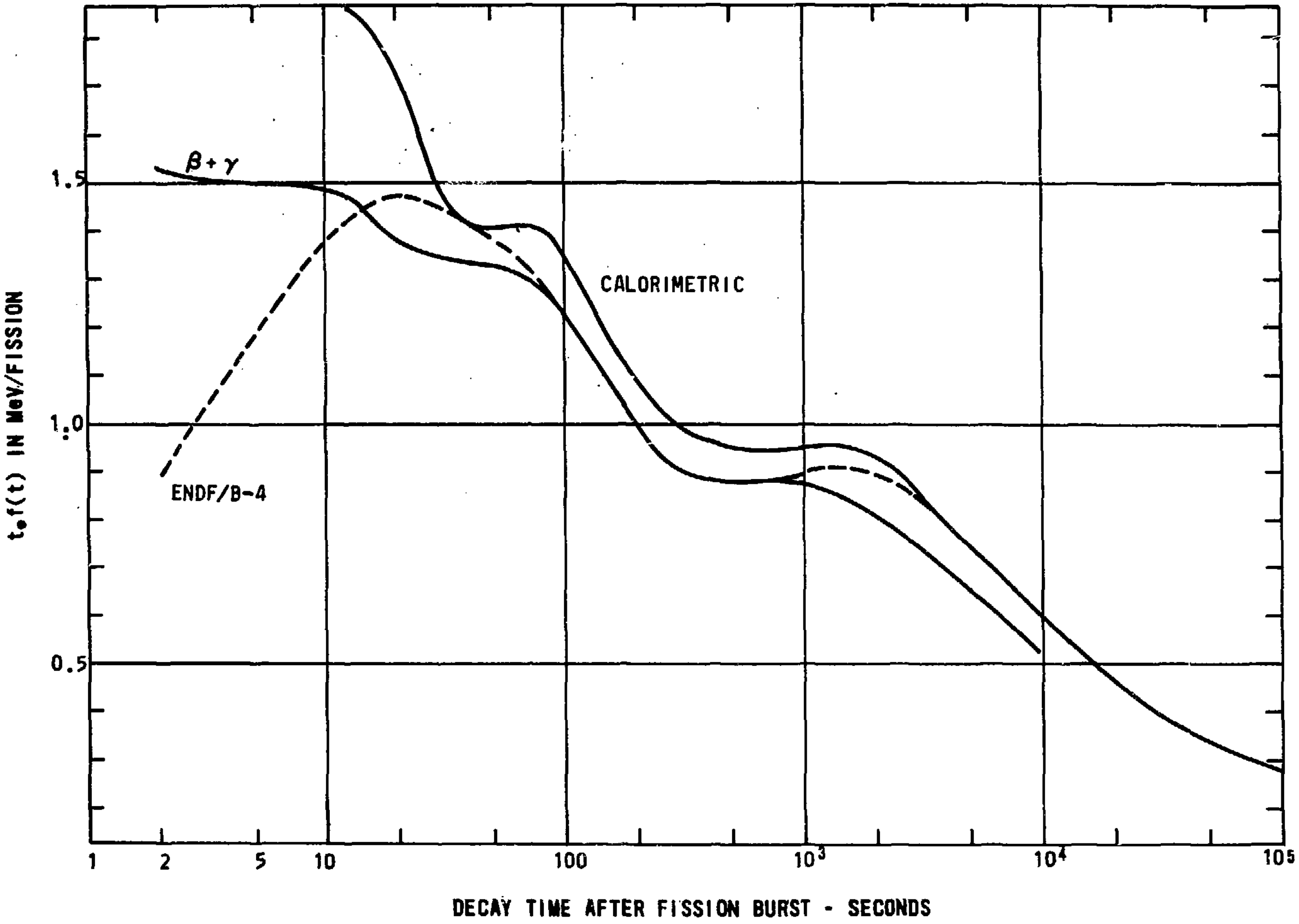

Fig. 1 - Comparison of Measured and Calculated Decay Power Following a Fission Burst

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