REVIEW OF NUCLEAR DATA OF RELEVANCE
FOR THE DECAY HEAT PROBLEM

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ABSTRACT

The decay data ($T_{\frac{1}{2}}$, Q_β, $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$) for fission-product nuclides are reviewed, with emphasis on those nuclides important for decay-heat calculations in the region from ∿10 sec to ∿10^3 sec. Problems involved in deducing $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values for these, and hence for even more neutron-rich, nuclides are illustrated by the example of ^{87}Br.

INTRODUCTION

Most analyses of the fission-product decay-heat source term are carried out using a so-called "summation-calculation" approach. Although simple in concept, this approach requires an extensive and sophisticated base of evaluated nuclear data. In addition to the operating history of the fissioning system, one needs the capture cross sections for, and the independent fission yields of, each of the fission products considered to be present. For each of the (typically) many hundreds of such nuclides, the following decay data are needed: nuclide half-life; the possible decay modes and their probabilities; and the average energies per decay of the emitted radiations. Since many of these nuclides lie far off the line of beta-stability, some of their decay properties have not been determined experimentally --values for them have to be obtained from other, usually theoretical, considerations. Furthermore, the average decay energies are almost never determined directly; they are computed from other measured features of the decay scheme, which may introduce systematic errors into their values, as discussed, e.g., in Ref. [1].

In spite of these complicating factors, the various summation codes are able to give a generally good description of the decay-heat source term for a variety of fissioning nuclides, as discussed in, e.g., Ref. [2]. However, careful analysis reveals that significant, systematic differences between calculation and experiment still exist, particularly at short cooling times, suggesting that there are deficiencies in some of the data. Numerous studies over the past several years have been carried out to determine the nature of these deficiencies and to correct, or at least compensate, for them. These efforts have been greatly assisted by developments that have taken place outside the area of decay heat. Foremost among these is the increasing use of on-line isotope separation as a tool for the study of the decay properties of short-lived fission products. It has also been recognized that such information is of great importance in nuclear astrophysics, where it can make possible realistic tests of models of nucleosynthesis in stellar environments (see, e.g., Ref. [3]). This confluence of experimental capability and scientific relevance has led to a resurgence of interest in the short-lived fission products, one category of neutron-rich nuclei important for nuclear astrophysics, and has produced a large amount of new information.

Consequently, it is appropriate to once again examine the fission-product decay data, to see to what extent these new developments lead to an improved ability to calculate the decay-heat source term. In this paper, we review selected aspects of this information. First, we briefly discuss nuclide half-lives, population of isomeric states in β^- decay, and Q_β values and average β- and γ-decay energies. (Other important data, namely independent fission yields, fission-product capture cross sections and delayed-neutron emission probabilities, lie outside the scope of the present discussion and are not treated.) Following this, we illustrate, using a specific case, some of the problems that occur when decay-scheme data are used to deduce average decay-energy values for short-lived nuclides. The need for a close interplay between experiment and theory to overcome these problems is pointed out.

REVIEW OF SELECTED DECAY DATA

That region of the Nuclide Chart which contains the fission-product nuclides included in the ENDF/B-V Fission-Product File is illustrated in Fig. 1. The region of nuclides covered differs somewhat in the various national nuclear data files, but that shown in Fig. 1 is typical and adequately covers those fission products important for decay heat. In Fig. 1, each square represents a specific nuclide, with the horizontal bar(s) within a given square indicating the existence of an isomeric state (or states) in the nuclide with that (Z,N) value. Stable isotopes are indicated by a solid black filling.

In the present discussion, we have chosen to dwell mostly on those nuclides whose contribution to the decay-heat source term is greatest in the time interval from a few tens of seconds to $\sim 10^3$ seconds, the one of most importance for assessing postulated loss-of-coolant accidents (LOCA) in operating fission reactors. These have been chosen, somewhat arbitrarily, from the results of various sensitivity studies (see, e.g., Refs. [4,5]), including that carried out for the ENDF/B decay-data evaluation effort; they are indicated by the cross-hatched areas in Fig. 1. Their decay data are usually less complete and accurate than those of nuclides closer to beta stability. They also present many opportunities for carrying out comparisons of various experimental techniques, as well as comparisons of experiment and theory as a means assessing the reliability of the latter for predicting the nuclear properties of even more neutron-rich, less well studied, nuclides.

For these latter nuclides very little decay data relevant to decay heat are available (generally at most a half-life and a few observed γ rays). Most of them have rather short half-lives and contribute to the decay-heat source term only at quite short cooling times and, consequently, are not very

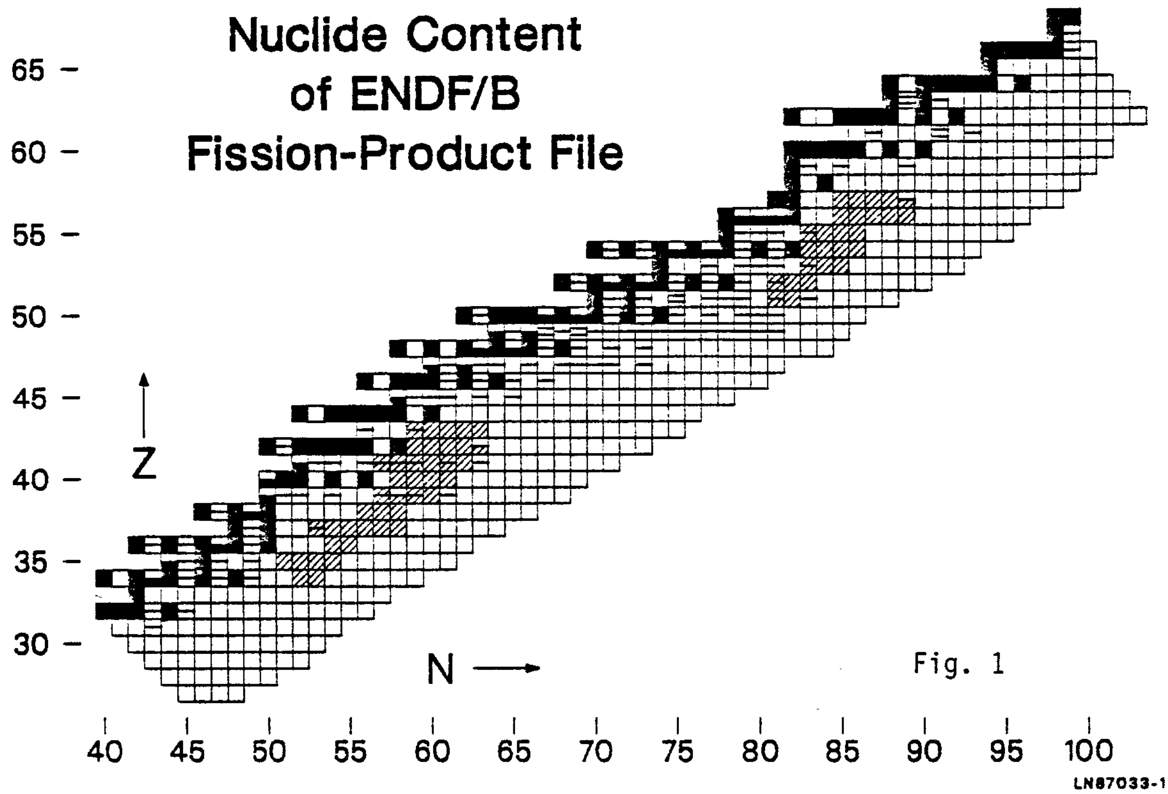

Fig. 1

important in LOCA assessment, although many of them contribute to "burst" irradiation situations. Here, the role of nuclear theory in providing values for the relevant and largely unknown decay data is most important and the resultant information is, hence, the most uncertain.

Nuclide Half-Lives

The present status of half-life data appears adequate for most decay-heat applications. For the isotopes of Zn - Sr and Ag - Ba, half-lives have been measured for nuclides up to within a few (∿2-3) mass numbers of the right-hand boundary of the region shown in Fig. 1. For the elements La through Sm, there is a gap of ∿4-5 isotopes between the heaviest studied nuclide and this boundary. These gaps in measured values are not very important for decay heat; and the cross-hatched nuclides lie well within the region of measured values. For the elements Y through Pd (the "refractory" elements), the situation is not quite so complete, although even here the measured values extend somewhat beyond the cross-hatched nuclides to, e.g., Y-102, Zr-104 and Nb-106. There are as yet no measured half-lives for the Ni and Co isotopes in Fig. 1, but these are not particularly important ones for decay heat.

For estimating half-life values for the unmeasured cases, two extensive sets of theoretical half-life values have been published [6, 7]. It has been observed (see, e.g., Ref. [8]) that the model of Ref. [6] tends to overestimate, while that of Ref. [7] tends to underestimate, the half-lives of nuclides far from beta stability. However, especially considering the relatively short extrapolations required to cover all the nuclides in Fig. 1, judicious use of these two compilations should be able to produce half-lives for the unmeasured nuclides that are sufficiently accurate for most decay-heat studies. (In a related development, Kratz [9] has recently been able to compute half-lives in reasonable agreement with experiment for several isotopic sequences of highly neutron-rich nuclides.)

Population of Isomers in Beta Decay

When a nuclide contains one (or more) isomers, it is necessary to know to what extent each of those "isomers" is populated in the beta decay of the parent. As discussed in many places (see, e.g., Refs. [4, 5]), errors in the assumed β^- population of such isomers can have dramatic effects on the predicted decay heat.

The status of information regarding the population of several "important" isomer pairs in β^- decay is as follows:

Y-96: The existence of two isomers in Y-96, having half-life and $I\pi$ values of 6.2 s, 0^-, and 9.6 s, (3+), with the former being the ground-state, is well established. No population of the 9.6-s activity is reported, although the Y-96 level scheme is such that it might be possible to populate (perhaps weakly) this state. The location of a 2.3-min isomer is an open question at this time. The reported existence of this activity led Tasaka [4] to consider Y-96 as an "important" nuclide at short decay times. However, no further information regarding this activity has been presented, and it is tempting to assume either that it does not exist or that it does not occur in Y-96. In any event, it is not populated appreciably in the Sr-96 decay.

Nb-98: The 2.86-s ground-state activity ($I\pi$=1+) is fed in the Zr-98 decay. Any feeding of the 51-min, $(5)^+$ isomer in this decay is now believed to be <1%.

Nb-99: Two isomers, with half-lives and $I\pi$ values of 15 s, $9/2^+$, and 2.6 min, $1/2^-$, are known [10]. The 2.6-min state lies ~365 keV above the ground state. From the intensity relationships within the Zr-99 decay scheme, we compute that ~39% of the Zr-99 β-decays feed the 2.6-min isomer and ~61% feed the 15-s ground state.

Nb-100: Perhaps the most challenging situation involves the isomers in Nb-100. At present, it is definitely established that activities with half-lives of 1.5 s and 3.1 s are associated with Nb-100. From a study of the decay of the 3.1-s activity [11], Keyser et al. report Q_β=6.745±0.075 MeV. From their revised Q_β value of 6.215±0.060 MeV for the 1.5-s decay, they conclude that the 3.1-s activity is an isomer and that it occurs at ~0.5 MeV in Nb-100. The available evidence suggests that it is not appreciably populated in the Zr-100 decay. Over the years, activities with half-lives of 12 min and 3 min have been assigned to Nb-100. Subsequent experiments have not confirmed these assignments and, again, it is tempting to disregard them in decay-heat calculations. However, because of the potential contribution of such activities to the decay-heat source term, one needs to clear up the question of the existence (and nuclide assignment) of these activities.

Decay Energies

The $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values for each nuclide are essential data for decay-heat calculations. The Q_β values are also quite important, even though they do not enter explicitly into such calculations, since they represent (through the relation $Q_\beta = \langle E_\beta \rangle + \langle E_{\bar{\nu}} \rangle + \langle E_\gamma \rangle$) an upper limit on how much energy is available to be released. Knowledge of this "upper limit" is especially important for those nuclides whose decay schemes are either unknown or are incomplete.

Those nuclides in Fig. 1 having measured Q_β values are considerably fewer than those for which half-life data are available. While in the extensively studied Rb and Cs isotopic chains, the heaviest of the measured nuclides (Rb-99 and Cs-147, according to the Audi-Wapstra Midstream Mass Evaluation [13]) approach to within 2 and 3 mass units, respectively, of the heavy-mass boundary in Fig. 1, for many elements gaps of as many as 12 nuclides occur between the heaviest investigated isotope and its "boundary nuclide". Consequently, the role of theoretically determined Q_β values in decay-heat calculations is more important than that of the estimated half-life values, mentioned above. The Q_β values are linked to atomic-mass differences, and since an enormous amount of work has been devoted over the years to these latter quantities, there are a number of "mass formulas" in existence, from which Q_β predictions can be made. However, these generally disagree among themselves for nuclei far from the line of beta stability; and there is thus uncertainty regarding which, if indeed any, of these is the "best" one to use. Haustein is presently conducting an extensive review of a number of these formulations and how well they agree with the available data. One can hope that the results of this study will shed light on this subject. As an essential tool for his work, he has available the 1986 "Midstream" evaluation by Audi and Wapstra [13], which provides an excellent base, as of about April, 1986, of evaluated experimental data on the atomic masses (and hence of Q_β values).

In Table I, we summarize the Q_β, $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ data for those nuclides we have called attention to in Fig. 1. Column 1 gives the nuclide and its nominal half-life. For each nuclide, three lines of data are given. The first line contains the Q_β values, and the second and third lines, respectively, give the $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values. Columns 3 through 8 present this information, as contained in several compilations. These are: K. Tasaka [4]; the UK Fission Product Decay Data File [14]; the Japanese JNDC Nuclear Data File [15]; the French CEA File [16]; the US File ENDF/B-V [17]; and the Table of Radioactive Isotopes [18]. Since the experimental Q_β values used in Refs. [17] and [18] were taken from the 1977 [19] and the 1983 [12] Atomic Mass Evaluations, respectively, we have listed the $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values from these two references in the corresponding columns (7 and 8, respectively). Thus columns 7 and 8 summarize the contents of ENDF/B-V and of the Table of Radioactive Isotopes, while also allowing a comparison of the Q_β values in these two Atomic Mass Evaluations with each other and with those in the 1986 midstream evaluation (column 9). Column 2 gives, for comparison, the directly measured $\langle E_\beta \rangle$ values of Aleklett and Rudstam [20].

Theoretical Q_β values are needed where no measurements exist, and to see how well mass formulas agree with experiment for these "measured" nuclides, we have included three such formulations. These are those of Ando _et al_. [21], based on the 1977 atomic mass evaluation [19], containing two treatments of the shell term, the latest version of the Möller-Nix mass formula [22], and a recent formulation [23] with a different approach for treating the nuclear compressibility.

TABLE I - Comparison of Q_β values and average decay energies (in MeV) for selected fission-product nuclides. For each nuclide, identified by element, isotope and nominal half-life, the data given are Q_β (first line), $\langle E_\beta \rangle$ (second line) and $\langle E_\gamma \rangle$ (third line). Quantities in parentheses represent the uncertainty in the least significant figure (or figures) of the associated value. Numbers in square brackets give the appropriate references. The symbols T, S and β refer to information derived from theoretical calculations, systematics and measured β strength-function data, respectively.

Nuclide	Studsvik [20]	Tasaka [4]	UKFPDD-2 [14]	JNDC [15]	CEA [16]	MASS EVALUATIONS: 1977 a) [19]	MASS EVALUATIONS: 1983-5 b) [12]	MASS EVALUATIONS: 1986 [13]	MASS CALCULATIONS: JNDC [21] const.	MASS CALCULATIONS: JNDC [21] lin.	MASS CALCULATIONS: Möller et.al. LANL [22]	MASS CALCULATIONS: Möller et.al. LBL [23]
Se-86		3.386T		5.100	5.100	5.100(S)	5.100(120)	5.100	5.019	5.479	5.46	5.31
15.s		0.993T	1.420T	1.350	1.209T	1.859T						
		1.015T	1.020T	1.964	2.308T	1.074T						
Se-87		8.000T		7.270	7.556		7.170(S)		7.385	7.380	8.37	8.19
5.6s		2.553T	2.500T	2.079	2.840T	2.539T						
		2.400T	1.738T	2.644	2.230T	1.713T						
Br-86		7.300		7.300	7.610	7.300(400)	7.620(60)	7.620	7.510	7.044	8.05	7.91
55.7s	1.92(11)	1.952	1.775	1.947	1.932	1.780	1.93					
		2.923	3.318	2.936	3.252	3.300	3.26					
Br-87		6.526		6.500	6.830	6.500(S)	6.830(120)	6.850	6.806	6.462	6.99	6.85
55.7s	1.20(6)	2.136	1.924	1.520	1.628	2.496	1.87					
		1.726	2.567	3.337	3.169	1.554	4.08					
Br-88		8.200		8.600	7.679	8.600(S)	8.970(130)	8.970	9.179	8.358	10.07	9.90
16.7s	1.63(7)	2.543	2.521	2.336	2.468	2.540	2.78					
		2.614	2.540	3.447	2.528	3.000	3.07					
Br-89		7.700T		8.040	7.340		8.300(S)		8.191	8.000	8.51	8.32
4.37s	2.32(12)	2.450T	2.815T	2.373	2.814T	2.631						
		2.310T	1.982T	2.768	0.161T	2.221	1.67					
Kr-90		4.390		4.377	4.377	4.390(30)	4.390(30)	4.403	4.145	4.380	4.65	4.49
32.3s		1.305	1.301	1.338	1.302	1.298	1.31					
		1.344	1.295	1.236	1.289	1.325	1.24					
Kr-91		5.080		6.200	6.200	6.200(100)	6.420(80)	6.416	6.525	6.182	7.12	6.94
8.6s	1.53(7)	2.056	1.984	1.871T	1.966	1.941	2.08					
		0.472	1.742	1.990T	1.745	1.733	1.75					
Rb-90		6.320		6.360	6.320	6.360(60)	6.589(12)	6.593	6.792	6.406	7.53	7.41
2.55m		1.659	1.862	1.992	1.857	2.203	1.98					
		2.660	2.172	2.164	2.164	1.062	1.85					
Rb-90m												
4.3m		1.929	1.219	1.388	1.265	1.356	1.40					
		2.145	3.211	3.350	3.207	3.098	3.30					
Rb-91		5.680T		5.700	5.700	5.700(40)	5.867(7)	5.866	5.805	5.795	6.27	6.13
58.s	1.36(7)	1.762T	1.509	1.476	1.576	1.497	1.58					
		1.704T	2.230	2.296	2.186	2.225	2.34					
Rb-92		8.180		7.770	8.049	7.770(200)	8.120(12)	8.112	8.193	7.686	8.17	7.98
4.5s	3.46(23)	3.697	3.459	2.856	3.499	3.481	3.53					
		0.214	0.261	1.556	0.520	0.261	0.537					
Rb-93		7.330T		7.450	7.260	7.360(70)	7.443(13)	7.472	7.236	7.282	7.00	6.79
5.8s	2.59(14)	2.324T	2.916	2.405	2.657	2.605	2.71					
		2.199T	0.846	2.063	1.393	1.320	1.42					
Rb-94		10.140		10.140	9.525	9.500(S)	10.307(27)	10.318	9.933	9.700	9.64	9.44
2.7s	2.51(13)	3.870	3.010T	2.716	3.081	2.796β	3.24					
		1.529	1.981T	3.575	2.706	3.278β	2.74					
Rb-95		8.600T		8.590	9.260	8.590(300)	9.280(60)	9.237	8.692	9.074	8.20	8.01
0.38s		2.758T	2.550T	3.102	2.765	3.116T						
		2.580T	1.972T	1.887	3.192	2.478T	0.612					
Sr-94		3.350		3.420	3.512	3.420(70)	3.512(5)	3.512	3.249	3.356	3.05	2.87
75.s	0.91(3)	0.870	0.870	0.810	0.848	0.898	0.835					
		1.242	1.242	1.433	1.427	1.242	1.43					
Sr-95		6.110T		6.090	6.060	6.090(90)	6.120(60)	6.164	5.948	5.881	5.80	5.68
25.s	1.92(9)	1.908T	2.264	2.132	2.087	2.113T	2.30					
		1.833T	1.041	1.348	1.341	1.397T	1.02					
Sr-96		4.122T		5.360	5.413	5.360(100)	5.416(20)	5.420	4.706	5.180	4.41	4.27
1.1s		1.219T	1.352T	1.962	2.004	1.884T	1.99					
		1.237T	1.120T	0.959	0.924	1.128T	0.932					
Y-96		6.800T		7.020	7.123	7.020(100)	7.140(40)	7.140	7.120	6.798	7.63	7.36
6.2s	2.83(15)	c)	3.256	2.656T	3.035	3.147	0.149					
			0.015	1.206T	0.398	2.600	0.001					
Y-96m												
9.6s			1.747	1.327T	1.388	1.107	0.005					
			4.038	3.910T	3.974	4.031	3.97					
Y-97		5.138T		6.670	6.648	6.670(130)	6.680(60)	6.680	5.881	5.919	5.74	5.51
3.7s		1.579T	2.159	2.472	2.142	2.154	2.16					
		1.542T	1.823	1.231	1.806	1.800	1.83					

TABLE I - (continued)

Nuclide	Studsvik [20]	Tasaka [4]	UKFPDD-2 [14]	JNDC [15]	CEA [16]	MASS EVALUATIONS 1977 a) [19]	MASS EVALUATIONS 1983-5 b) [12]	MASS EVALUATIONS 1986 [13]	MASS CALCULATIONS JNDC [21] const.		MASS CALCULATIONS Möller et.al. lin. [22]	MASS CALCULATIONS Möller et.al. LANL [23]	MASS CALCULATIONS Möller et.al. LBL
Y-98		8.058T		8.980	8.890	8.100(S)	8.910(60)	8.910	8.551	8.252	8.33	8.14	
0.64s		d)	3.111	3.216	3.671	2.983	3.74						
			0.845	2.014	0.930	0.814	0.907						
Y-98m													
2.0s		d)	1.809	2.989	2.548	1.806	2.63						
			3.100	2.596	3.049	3.151	3.04						
Y-99		6.529T		6.390	7.610	6.390(200)	7.610(80)	7.620	6.773	6.387	6.85	6.68	
1.5s		2.051T	2.614	2.375	3.248	2.606	3.12						
		1.959T	0.625	1.147	0.652	0.611	0.818						
Zr-98		2.240T		2.239	2.239	2.239(21)	2.240(20)	2.245	2.039	2.060	2.01	1.83	
31.s		0.620T	0.909	0.837T	0.906	0.906	0.907						
		0.672T	0	0.165T	0	0	0.002						
Zr-99		4.628T		4.328	4.590	4.460(100)	4.590(70)	4.538	4.711	4.507	4.77	4.55	
2.1s		1.408T	1.501	1.409T	1.858	1.487	1.55						
		1.388T	0.813	1.184T	0.842	0.823	0.860						
Zr-100		3.100T		3.359	3.360	3.360(150)	3.330(70)	3.339	2.933	2.637	3.21	3.06	
7.1s		0.899T	0.737T	1.114T	1.090	1.192T							
		0.930T	0.632T	0.698T	0.698	0.694T							
Zr-101		6.500		5.900	6.100	5.900(S)	5.780(120)	5.780	6.029	5.625	5.87	5.72	
2.0s		2.597	2.817	2.160	2.788	2.212T							
		0.765	0.353	1.091	0.040	1.527T							
Nb-98		4.600		4.585	4.585	4.585(6)	4.586(6)	4.585	5.063	4.960	5.06	4.91	
2.9s		1.985	1.972	1.996T	1.958	1.959	1.96						
		0.116	0.125	0.099T	0.080	0.080	0.091						
Nb-98m													
51.m		0.891	0.916	0.779	0.852	0.834	0.789						
		2.414	2.416	2.820	2.717	2.590	2.71						
Nb-99		3.736		3.624	3.640	3.624(16)	3.640(13)	3.639	3.824	3.891	3.44	3.28	
15.s		1.510	1.249	1.275T	1.579	1.617T							
		0.236	0.179	0.622T	0.236	0.168T	0.168						
Nb-99m													
2.6m		1.367	0.935	1.176	1.443	1.346T	1.47						
		0.905	1.412	1.716	0.752	0.814T	0.755						
Nb-100		6.500T		6.230	6.230	6.230(130)	6.240(30)	6.257	6.503	6.462	6.21	5.99	
1.5s		2.041T	2.060	1.948T	2.075T	2.187T							
		1.950T	1.920	1.846T	2.075T	1.385T							
Nb-100m													
3.1s		2.041T	2.119T	1.696T	2.640	2.187T							
		1.950T	1.366T	2.364T	0.949	1.385T							
Nb-101		4.600		4.570	4.630	4.570(100)	4.630(70)	4.563	4.727	4.601	4.64	4.46	
7.1s		1.847	1.861	1.686	0	1.848							
		0.400	0.284	0.720	0	0.317							
Nb-102		7.000T		7.200	7.200	7.200(S)	7.210(70)	7.209	7.381	7.633	7.05	6.88	
4.3s		2.311T	2.487T	2.832	2.020T	2.594T							
		2.100T	1.688T	1.461	2.650T	1.964T							
Nb-102													
1.3s			2.487T	2.832	2.400T	2.594T							
			1.688T	1.461	3.400T	1.964T							
Nb-103		5.507T		5.200	5.500	5.200(S)	5.500(120)	5.520	5.922	5.695	5.72	5.56	
1.5s		1.704T	1.736T	2.111	1.833T	1.931T							
		1.652T	1.382T	0.982	1.833T	1.286T							
Mo-101		2.820		2.811	2.812	2.811(24)	2.812(24)	2.824	2.937	2.953	2.53	2.36	
14.6m		0.576	0.506	0.511	0.528	0.585	0.512						
		1.337	1.502	1.553	1.513	1.386	1.51						
Mo-102		1.040T		1.040	1.013	1.040(S)	1.014(23)	1.010	1.159	1.132	1.07	0.90	
11.3m		0.254T	0.362	0.351T	0.350	0.440	0.351						
		0.312T	0.019	0.047T	0.018	0	0.019						
Mo-103		4.400T		4.300	4.000	4.300(S)	4.000(S)	3.841	4.265	4.240	3.87	3.69	
68.s		1.326T	1.306T	1.144	1.183T	1.326T							
		1.320T	0.988T	1.134	1.226T	0.800T							
Mo-104		2.400T		2.200	2.200	2.200(S)	2.000(S)	2.120	2.355	2.341	2.48	2.34	
60.s		0.671T	0.548T	0.623	0.912	0.581T	0.685						
		0.720T	0.488T	0.585	0.147	0.358T	0.147						
Mo-105		5.500T		5.400	5.000	5.400(S)	5.000(S)	4.990	5.560	5.586	5.13	4.95	
35.6s		1.702T	1.719T	1.741T	0	1.684T							
		1.650T	1.396T	1.436T	1.788	1.087T							
Tc-102		4.500		4.710	4.525	4.500(S)	4.526(10)	4.530	4.365	4.423	4.05	3.93	
5.28s		1.752	1.488	1.154T	1.945	1.700	1.95						
		0.491	0.488	1.775T	0.081	0.469	0.088						

TABLE I - (continued)

Nuclide	Studsvik [20]	Tasaka [4]	UKFPDD-2 [14]	JNDC [15]	CEA [16]	MASS EVALUATIONS 1977 a) [19]	MASS EVALUATIONS 1983-5 b) [12]	MASS EVALUATIONS 1986 [13]	MASS CALCULATIONS JNDC [21] const.	MASS CALCULATIONS JNDC [21] lin.	MASS CALCULATIONS Möller et.al. LANL [22]	MASS CALCULATIONS Möller et.al. LBL [23]
Tc-102m												
4.35m		1.020	0.717	0.649T	0.780	0.940	0.780					
		2.554	2.497	2.848T	2.377	2.377	2.49					
Tc-103		2.200T		2.350	2.654	2.350(100)	2.654(11)	2.659	2.590	2.531	2.38	2.25
54.2s		0.607T	0.783	0.704T	0.987	0.770T	0.983					
		0.660T	0.233	0.553T	0.254	0.423T	0.238					
Tc-104		5.400		5.620	5.620	5.400(S)	5.620(70)	5.603	5.702	5.605	5.10	4.92
18.3m		1.616	1.591	1.403T	1.454	1.582	1.61					
		1.681	1.728	2.131T	2.245	1.940	2.00					
Tc-105		3.400T		3.400	3.800	3.400(200)	3.800(S)	3.582	3.794	3.635	3.66	3.54
7.6m		0.998T	1.158	1.169T	1.337	1.148T	1.43					
		1.020T	0.459	0.612T	0.795	0.675T	0.539					
Tc-106		6.500T		6.300	6.950	6.300(S)	6.700(S)	6.536	7.006	6.812	6.29	6.12
36.s		2.041T	2.109	2.104	2.105	2.227T						
		1.950T	2.235	2.226	2.225	1.511T						
Sb-132		5.600		5.600	5.530	5.600(200)	5.490(80)	5.492	6.639	5.580	6.52	6.40
4.15m		1.347	1.353	1.111T	1.268	1.382	1.34					
		2.406	2.363	2.907T	2.573	2.600	2.59					
Sb-132m												
2.8m		1.290	1.272	1.197T	1.220	1.300	1.24					
		2.529	2.492	2.728T	2.627	2.631	2.61					
Sb-133		4.000T		3.863	3.950	3.950(200)	3.950(200)	3.950	5.453	4.401	5.33	5.21
2.36m		1.173T	0.665	0.748	0.658	1.062						
		1.200T	2.221	1.954	2.743	1.220						
Te-133		2.960		2.970	2.970	2.970(60)	2.920(70)	2.918	3.638	2.909	3.05	2.97
12.4m		0.806	0.820	1.022	0.708	0.818	0.797					
		0.930	0.983	1.194	1.200	0.929	0.954					
Te-133m												
55.4m		0.837	0.520	0.369	0.346	0.672	0.600					
		0.867	0.903	1.759	1.834	2.308	1.70					
Te-134		1.400		1.560	1.560	1.300(S)	1.560(90)	1.560	2.452	1.728	1.88	1.79
41.8m		0.153	0.296	0.205	0.246	0.268	0.243					
		0.918	0.858	0.894	0.849	0.877	0.858					
Te-135		6.000T		6.200	5.970	6.200(250)	5.960(100)	5.951	6.398	6.123	5.84	5.74
19.2s		1.871T	2.436	2.173	2.464	2.399β						
		1.800T	0.697	1.609	0.567	0.736β						
I-136		6.980		7.000	7.000	7.000(100)	6.930(50)	6.879	7.657	7.024	6.92	6.82
84.s	1.97(8)	2.111	1.980	1.700T	2.034	1.968	1.97					
		2.173	2.394	3.066T	2.479	2.378	2.46					
I-136m												
45.s	2.11(12)	2.238	2.148	1.760T	2.145	2.130	2.19					
		1.906	2.145	2.942T	2.132	2.000	2.14					
I-137		5.800T		5.600	5.404	5.500(200)	5.880(80)	5.876	6.455	5.560	5.93	5.84
24.5s	2.25(11)	1.803T	1.515T	1.798	1.100T	2.287β	1.96					
		1.740T	2.029T	1.136	2.200T	0.971β	1.14					
I-138		8.000		8.300	6.898	8.300(S)	7.820(70)	7.820	8.521	7.398	8.77	8.62
6.4s	2.27(13)	3.272	2.812	3.293	2.545	2.255T	2.59					
		0.782	1.649	1.023	1.448	1.982T	1.89					
Xe-137		4.347		4.344	4.343	4.344(23)	4.177(8)	4.173	4.260	4.226	3.90	3.84
3.82m	1.73(3)	1.801	1.789	1.787	1.780	1.774	1.70					
		0.182	0.190	0.188	0.180	0.189	0.196					
Xe-138		2.830		2.830	2.830	2.740(50)	2.770(40)	2.786	3.056	2.847	2.86	2.80
14.1m	0.80(10)	0.662	0.676	0.645	0.678	0.635	0.639					
		1.144	1.126	1.217	1.124	1.096	1.13					
Xe-139		4.880		5.020	5.020	4.880(60)	5.020(60)	5.020	5.124	4.778	5.47	5.38
39.7s	1.72(6)	1.749	1.736	1.665T	1.701	1.702	1.78					
		0.830	0.890	1.015T	0.885	0.760	0.894					
Xe-140		3.510		4.060	4.060	4.060(60)	4.060(60)	4.063	3.941	3.705	4.45	4.37
13.6s	1.52(5)	0.881	1.223	1.058T	1.278	1.181	1.22					
		1.360	1.117	1.468T	1.143	1.210	1.15					
Cs-138		5.290		5.340	5.335	5.500(S)	5.377(22)	5.376	5.413	5.454	5.58	5.53
32.2m	1.22(12)	1.213	1.202	1.247	1.269	1.202	1.24					
		2.364	2.362	2.331	2.361	2.361	2.36					
Cs-138m												
2.9m		0.342	0.379	0.283T	0.342	0.386	0.319					
		0.544	0.525	0.707T	0.401	0.540	0.420					
Cs-139		4.290		4.290	4.204	4.290(70)	4.213(5)	4.214	4.210	4.078	4.30	4.25
9.27m	1.73(5)	1.714	1.702	1.699	1.647	1.686	1.65					
		0.307	0.308	0.329	0.329	0.328	0.329					
Cs-140		5.700		6.170	6.177	6.050(250)	6.218(13)	6.220	6.283	6.018	7.26	7.12
63.7s	1.89(4)	1.640	1.739	1.558T	1.703	1.649	1.75					
		1.873	2.105	2.398T	2.285	2.300	2.26					

TABLE -I (continued)

Nuclide	Studsvik [20]	Tasaka [4]	UKFPDD-2 [14]	JNDC [15]	CEA [16]	MASS EVALUATIONS 1977 a) [19]	1983-5 b) [12]	1986 [13]	MASS CALCULATIONS JNDC [21] const.	lin.	Möller et.al. LANL [22]	LBL [23]
Cs-141		4.990T		5.190	5.038	4.980(80)	5.256(14)	5.260	5.102	4.878	5.45	5.32
24.9s	1.68(7)	1.530T	1.791	1.504T	1.769	1.912	1.88					
		1.497T	0.918	1.445T	0.978	0.800	1.01					
Ba-141		3.010		3.015	3.230	3.030(50)	3.230(27)	3.251	3.182	3.183	4.01	3.92
18.3m		0.868	0.874	0.821	0.984	0.883	0.967					
		0.834	0.839	0.844	0.816	0.888	0.847					
Ba-142		2.200T		2.200	2.200	2.200(100)	2.120(40)	2.180(20)	2.000	2.061	2.23	2.17
10.6m		0.607T	0.428	0.419	0.395	0.416	0.378					
		0.660T	1.013	1.069	1.069	1.013	1.04					
Ba-143		3.500T		4.300	4.250	4.300(S)	4.250(40)	4.221	4.186	4.331	4.34	4.27
14.5s		1.031T	1.649	1.458T	1.615	1.232β	1.72					
		1.050T	0.354	0.857T	0.982	1.006β	0.231					
Ba-144		2.900T		2.900	3.060	2.900(S)	2.970(90)	3.100	2.833	3.064	3.50	3.44
11.4s		0.833T	0.648T	0.833T	1.134	1.025β						
		0.870T	1.046T	0.948T	0.521	0.648β						
Ba-145		5.612T		5.100	4.950	5.100(S)	4.950(110)	4.910	5.126	5.227	5.37	5.25
4.0s		1.739T	2.025	1.757	2.027	1.531β	2.02					
		1.684T	0.292	1.159	0.444	1.315β	0.310					
La-142		4.517		4.517	4.517	4.517(6)	4.517(6)	4.515	4.565	4.523	5.85	5.74
1.54h		0.847	0.947	0.915	0.864	0.896	0.842					
		2.394	2.400	2.523	2.374	2.750	2.49					
La-143		3.321		3.300	3.290	3.300(80)	3.290(50)	3.416	3.384	3.327	3.56	3.50
14.1m		0.972	1.329	1.341	1.271	1.085T	1.31					
		0.996	0.098	0.031	0.266	0.709T	0.097					
La-144		5.600		5.500	5.440	5.500(S)	5.600(110)	5.501	5.575	5.578	5.64	5.54
40.9s		1.510	1.468	1.466	1.372	1.461	1.61					
		1.940	1.836	2.097	2.169	1.824	2.17					
La-145		4.150		4.200	4.120	4.200(S)	4.120(90)	4.090	4.223	4.239	4.56	4.48
24.8s		1.060	1.479	1.093T	1.547	1.023β	1.48					
		1.520	0.656	1.525T	0.702	1.613β	0.643					
La-146		6.300T		6.300	6.380	6.300(S)	6.386(30)	6.530	6.520	6.402	6.38	6.25
6.27s		1.973T	1.768T	2.182	2.129	2.046T	2.16					
		1.890T	2.357T	1.345	1.518	1.728T	1.49					

a) The listed Q_β values are, in most cases, those that were used in the ENDF/B-V Fission Product File. The $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values are also those that appear in this File.
b) The $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values are those given in the Table of Radioactive Isotopes [18].
c) Only a 2.3 min activity was assumed to be present in Y-96.
d) Only a 0.3 s activity was assumed to be present in Y-98

We do not attempt here a detailed discussion of all the data in Table I. However, it is interesting to note the rather heavy reliance in the JNDC File on theoretical information, (where most other files list measured values), in an effort to overcome suspected problems with $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ data derived from complex decay schemes. Also, a number of Q_β values (e.g., Br-87, Br-88, Rb-90, Rb-95, Y-99) have changed markedly since the 1977 Atomic Mass Evaluation, and average-energy values derived from the earlier data will need to be suitably modified.

COMPLEX DECAY SCHEMES: THE EXAMPLE OF ^{87}Br

Br-87 ($T_{\frac{1}{2}}$ = 55.7 s) provides an informative example of the potential pitfalls of using even apparently well studied decay schemes to determine $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values when the Q_β's are large enough that regions of high level density in the daughter nucleus are populated. Although discussed in some detail elsewhere [24], the salient points are presented here. A recent exhaustive study [25] of Br-87 gave a considerably more detailed decay scheme than was previously available (summarized in the extant

Nuclear Data Sheets evaluation [26]). The average decay-energy values (in MeV) computed from these two sets of data are:

Reference	⟨E_β⟩	⟨$E_{\bar{\nu}}$⟩	⟨E_γ⟩	Sum	
[25]	1.653	2.140	3.338	7.131	
[26]	1.861	2.358	4.113	8.332	Q_β = 6.83±0.12
[26],rev.	2.095	2.764	2.828	7.687	

Ref.[25], naturally, reported many more levels and γ-ray transitions than did Ref. [26] and, hence, some differences in average decay-energy values is to be expected. However, a major contribution to these differences comes from the measured γ-ray emission probabilities, which are ∿30% smaller in Ref. [25] than in Ref. [26]. (If one uses these smaller P_γ values to recalculate the intensity balances in the decay scheme of Ref. [26], the values labelled "[26], rev." are obtained.) The following points should be noted:

- The study in Ref. [25] is exceptional - very few of the shorter-lived fission-product nuclides have been, or likely ever will be, studied in the detail that Br-87 now has been. It has led to significant changes in the previously available ⟨E_β⟩ and ⟨E_γ⟩ values, even though these were obtained from information that was certainly adequate for many purposes in nuclear-structure physics.
- The P_γ values in [25] and [26] are based on "directly" measured data. For most of the shorter-lived fission products, especially those farther from beta-stability, the P_γ values are either not known or derived from considerations other than a direct experimental determination.
- Br-87 is a relatively light nuclide and, even at Kr-87 excitation energies near the β-decay Q value, the level spacings are ∿ a few keV, so that discrete-line γ spectroscopy might (at least in principle) be able to identify all the emitted γ rays. For much heavier nuclides, however, the spacings of levels accessible to β decay are sufficiently small that this is no longer possible and, hence, accurate β-intensity distributions cannot be obtained in this manner.
- Br-87 is relatively close to beta-stability. Its relatively long half-life (55.7 s) and the ease with which it can be isotope separated make it a much simpler nuclide to study than the vast majority of short-lived fission products.

This discussion does not assume that the data in Ref. [25] are more accurate than those in Ref. [26] (although this is probably the case). Its purpose has been simply to point out that this more detailed information has led to significant changes in the decay data for Br-87, previously thought to be a well-studied nuclide, and that, consequently, the reliability of the decay schemes of other short-lived nuclides, where such highly detailed data are not (and may never be) available, needs to be questioned. These problems of fission-product decay data are being increasingly recognized, (see, e.g., [15,27]).

SUMMARY

The status of fission-product decay data for those nuclides close to the line of β-stability, where the level densities and Q_β values are low and the half-lives are relatively long, can be generally considered to be adequate for purposes of decay-heat calculations. As one moves further away from β-stability, the situation becomes more complicated. For half-lives, the situation can be regarded as being reasonably satisfactory over the range of fission-product nuclides illustrated in Fig. 1. Even though some of these do not yet have measured half-lives, reasonable estimates can be obtained through, e.g., extrapolation or interpolation, using the existing data together with presently known systematic properties of existing tables of theoretical values. As one moves farther from β-stability, the possibility of inaccurate and/or misassigned half-life values of course increases and the existence of isomeric states and knowledge of their relative population in β-decay becomes increasingly uncertain. However, these potential problems should not significantly affect decay-heat predictions for times important for LOCA assessments (although they may affect "burst-irradiation" calculations).

The data on Q_β values are considerably less extensive than those on half-lives and do not extend as far off the line of β-stability. The lack of such information thus has a more significant impact on decay-heat calculations. The new data contained in the 1986 "Midstream" mass evaluation should give an excellent summary of measured values, but the problem of reliably extrapolating to the unmeasured cases is a formidable one, judging from the frequently quite different predictions of different mass formulas (examples of which are shown in Table I). It is hoped that the critical evaluation of mass formulas currently in progress by Haustein will provide insights into which of them may be useful in this regard.

The determination of $\langle E_\beta \rangle$ and $\langle E_\gamma \rangle$ values presents the most serious challenge. Although considerable theoretical work on this problem has been carried out in conjunction with the JNDC data file [15,27], with rather impressive results [5], the average decay-energy problem still stands in need of additional work, which, we believe, requires a close interplay between experimental measurement and theoretical calculation [28]. Some promising starts along these lines have been reported by Kratz et al. [31]. At INEL, a comprehensive effort in this area, combining direct measurement of the β decay strength functions of selected "key" nuclides and theoretical calculations utilizing an approach similar to that of Ref. [31] but better suited for extrapolation, is getting underway, the results of which should contribute signigicantly to our understanding of the $\langle E_\beta \rangle$, $\langle E_\gamma \rangle$ values of the highly unstable fission-product nuclides.

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