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Assessment of the Impact of TAGS on Gamma Decay Heat for JEFF3.1 ^{235}U and ^{239}Pu

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Executive Summary

Decay heat prediction in thermal reactors with preliminary JEFF3 files has been performed by Mills and Parker. At the May 2005 JEFF meeting French studies indicated the split between heating from gammas and betas needed review to understand discrepancies from experiment.

Nichols notes that Total Absorption Gamma-ray Spectroscopy (TAGS) could help resolve the beta decay scheme and hence impact on the split between gamma and beta decay energy. He points to recent studies by Yoshida et. al. . These studies were based on TAGS measurements for the short lived isotopes of Rb, Sr, Y, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, and Eu and show a significant improvement in prediction of Pu-239 gamma decay heat at fast energies, when TAGS mean energies replace those in JEF2.2 for these fission products.

The average energies in JEF2.2 for many of these short lived fission products are taken from work by Rudstam et al. In the JEFF3.1 decay files, these average energies have been produced by summing the spectral emission data.

This paper describes a study carried out to assess the impact, on thermal gamma heating for U-235 and Pu-239, of applying TAGS mean gamma energies to the JEFF3.1 decay data. An assessment was also made of applying Rudstam mean gamma energies to JEFF3.1.

FISPIN10 calculations were preformed to obtain gamma energies from fission product decay following fission bursts in U-235 and Pu-239. The results for unmodified JEFF3.1 decay data, JEFF3.1 data with mean gamma energies from TAGS and JEFF3.1 data with mean gamma energies from Rudstam were compared with Tobias' evaluation of experimental data and with three sets of measured data.

The study found that the application of Rudstam data gave no improvement over the unmodified JEFF3.1. However, use of the TAGS data did result in a significant improvement for both U-235 and Pu-239.

It was noted that the Tobias data for U-235 were generally higher than the experimental data up to ~100s. This could have implications for the selection of the most appropriate dataset for decay heat prediction.

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1 Introduction

Decay heat prediction in thermal reactors with preliminary JEFF3 files has been performed by Mills and Parker [1]. At the May 2005 JEFF meeting French studies [2] indicated the split between heating from gammas and betas needed review to understand discrepancies from experiment.

Nichols [3] notes that Total Absorption Gamma-ray Spectroscopy (TAGS) could help resolve the beta decay scheme and hence impact on the split between gamma and beta decay energy. He points to recent studies by Yoshida et. al. [4]. These studies were based on TAGS measurements for some 48 short lived fission products [5] and show a significant improvement in prediction of Pu-239 gamma decay heat at fast energies, when TAGS mean energies replace those in JEF2.2 for these fission products.

The average energies in JEF2.2 for many of these short lived fission products are taken from work by Rudstam et. al. [6]. In the JEFF3.1 decay files, these average energies have been produced by summing the spectral emission data.

This paper describes a study carried out to assess the impact, on thermal gamma heating for U-235 and Pu-239, of applying TAGS mean gamma energies to the JEFF3.1 decay data. An assessment was also made of the effect of applying Rudstam's mean gamma energies to JEFF3.1.

The following outline method was used to carry out the study.

Experimental values of gamma decay heat following fission bursts in U-235 and Pu-239 were obtained from literature.

A fission product decay data library based on JEFF3.1 decay data was prepared for the FISPIN code [7] by Nexia Solutions.

The latest version 10 of the FISPIN code was applied to calculate total gamma decay heat following fission bursts in U-235 and Pu-239, using the JEFF3.1 fission product decay data library.

The calculations were repeated with the mean gamma emission energies for short lived isotopes of Rb, Sr, Y, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, and Eu replaced by values calculated from Greenwood's TAGS data [5]

A further set of calculations were carried out in which mean gamma emission energies for the selected nuclides were replaced by values from Rudstam [6] or from JEF2.2 [8].

The total gamma decay heat from the three sets of calculations were compared with experimental data.

2 Experimental Gamma Decay Heat Data

The last comprehensive validation of decay heat within the JEFF project is documented in chapter 9 of JEF report 17 [8]. This recommends that summation calculations, using modern data libraries and codes such as FISPIN, should compare results with one of the international standards rather than individual measurements. It also notes Tobias' standard [9] uses only measured data whereas the others incorporate summation calculations. This work accepts this recommendation and we compare our calculations with Tobias' standard.

It is noticeable that others compare their calculations with quality measurements, and in particular WPEC sub group 25 results [10] are compared with "YOYOI, LOWELL and ORNL". Recent CEA comparisons by Huynh Tan Dat [2] refer to Aktyama [11,12] {corresponding to YOYOI} and Dickens [13,14] {corresponding to ORNL}. The LOWELL points are currently assumed to refer to Nguyen et al's work [15]. This is the only reference we found dated after Tobias published his standard in 1989.

Tobias lists experimental references for gamma heating reproduced in Tables 1 and 2.

Table 1. Experiments in Tobias' fit to Gamma heating in U-235

Irradiation in s	Cooling Time	Uncertainty %		Reference
		Normal	Statistical	
1000	1 –50000	2.9	0.7 – 20.0	Friesenhahn and Lurie (1979)
20000	1 – 100000	2.9	0.5 – 3.8	"
86400	1 – 150000	2.9	0.5 – 2.7	"
3024000	1 – 200000	2.0	0.9 – 3.5	"
1	1.7-89.7	2.5	1.8-4.7	Dickens et al (1980)
10	10.7 – 595	2.5	1.3 – 2.9	"
100	70 – 9950	2.5	3.1 – 11.0	"
10	11 – 3200	3.2	2.9 – 4.6	Akiyama et al (1982a)
10	17 – 3800	4.0	2.3 – 4.5	"
100	70 – 18000	2.4	1.3 – 2.2	"
100	110 – 22000	2.5	1.1 – 2.0	"
20000	4 - 150000	2.0	3.5	Jurney et al (1979
4	10 – 270	3.0	6.3	Johansson (1987)
10	70 – 555	3.0	6.3	"
120	160 – 1340	3.0	6.3	"
Pulse	0.2 – 35	7.1	9.7	Fisher and Engle (1964)
Pulse	1.2 – 1800	12.0	10.6	Maienschein et al (1958)
Pulse	85 – 260000	10.0	11.2	Bunney and Sam (1970)

Table 2. Experiments in Tobias' fit to Gamma heating in Pu-239

Irradiation in s	Cooling Time	Uncertainty %		Reference
		Normal	Statistical	
1000	1 – 5500	3.0	0.6 – 1.9	Friesenhahn and Lurie (1979)
86400	1 – 130000	1.8	0.3 – 1.1	"
1	1.7 – 110	2.0	2.9 – 5.6	Dickens et al (1981)
5	17 – 800	2.0	1.3 – 4.1	"
100	250 – 9950	2.0	1.8 – 5.6	"
10	11 – 3200	3.5	2.7 – 4.4	Akiyama et al

Irradiation in s	Cooling Time	Uncertainty %		Reference
		Normal	Statistical	
				(1982a)
10	17 – 3800	3.6	1.7 – 3.6	"
100	950 – 22000	2.9	0.8 – 2.1	"
20000	4 – 140000	2.0	3.5 – 13.0	Jurney et al (1979)

Considering U-235; Akiyama et al (1982a) is Reference [11] and Dickens et al (1980) is Reference [14]. Considering Pu-239; Akiyama et al (1982a) is Reference [11] and Dickens et al (1981) is Reference [13]. Hence, Tobias has included measurements considered by the sub-group except the recent Lowell work.

3 TAGS Gamma Emission Energies

Total absorption gamma-ray spectroscopy (TAGS) was used by Greenwood et al [5] to obtain distributions of β- decay intensities for the short lived isotopes of Rb, Sr, Y, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, and Eu. A full list of nuclides considered is given in Table 3.

For each nuclide, Reference [5] defines decay intensities associated with quantum energy levels in the daughter nucleus. These are compared with values from then current Nuclear Data Sheets and hence collectively labelled ENSDF after the database [16] which contains current values of these data.

From these β- decay intensities, the mean gamma energy released per decay was calculated using the formula

$$E_\gamma = \sum_i [R(E_i)\cdot E_i] - \overline{E}_{conv}$$

with

$$R(E_i) = \frac{I_\beta(E_i)}{\sum_i I_\beta(E_i)}$$

where E_i is the level energy of the daughter nuclide, I_β is the relative intensity of the beta and $\overline{E}_{conv}$ is the mean energy of conversion electrons.

Reference [5] notes that considerable correction to the raw experimental data was made before the final tables were produced. It is also noted that in the ideal situation, the cascade gamma rays multiplied by their intensity should sum to the daughter level energy multiplied by the beta intensity, given there is no photon escape, no attenuation and no internal conversion etc. It is reasonable to assume that Greenwood et al have attempted to account for these effects in producing the tables. Since the paper compares values with ENSDF it is appropriate to assume these are the best estimation of the same quantities. Thus in calculating the mean gamma energies, the mean energies of the conversion electrons, taken from the JEFF3.1 decay data files, were subtracted.

The values of mean gamma energy calculated for the TAGS data are listed in Table 3. These are compared with values calculated from the information attributed to various Nuclear Data Sheets by Greenwood (Labelled ENSDF) and values taken from the JEFF3.1 decay data files.

4 Mean Gamma Energies from Rudstam/JEF2.2

In the JEF2.2 decay data files, the mean beta and gamma decay energies for many of the nuclides were taken from the work of Rudstam et al [6]. In JEFF3.1, these Rudstam values have not been used and the mean decay energies have been formed from the sum of spectral emission data. Thus, Rudstam provides a further set of measured mean gamma energy values that are not included in JEFF3.1.

Rudstam's work covered a restricted mass range and thus not all the nuclides under consideration were available from Reference [6]. The following nuclides were not covered in Rudstam's study.

Ce-148
Cs-138
Eu-158
La-142
Nd-149 Nd-151 Nd-153 Nd-154 Nd-155
Pm-152 Pm-153 Pm-154 Pm-155 Pm-156 Pm-157
Pr-146 Pr-148 Pr-149 Pr-151
Sm-157 Sm-158

For these missing nuclides, mean energy values were taken from the JEF2.2 decay data file.

The mean gamma energy values were extracted from the JEF2.2 decay data files for all the nuclides of interest. The values used were the mean electromagnetic radiation energies, parameter $\overline{E}_{EM}$ in Section 8.3 of Reference [17]. This value includes the X-rays as well as the gammas but an inspection of the evaluations confirmed that, in all cases, the X-ray contribution was not significant.

Those JEF2.2 decay data evaluations that use the Rudstam mean energy values are indicated by comments to this effect in the descriptive text. An inspection of the JEF2.2 decay data files indicated that, with the exception of Rb-90 and Sr-95, Rudstam's values had been adopted for all these nuclides.

Table 4 lists the mean gamma energies from JEF2.2 and Rudstam. This shows that, in the majority of cases, the JEF2.2 values were identical with Rudstam (where present). The exceptions were Ba-141, Ba-145 and Cs-140. For these nuclides, the comments in the JEF2.2 files state that the average energies were taken from private communication from Rudstam in 1990. It is probable that the JEF2.2 figures post-date those in Reference [5] and thus the JEF2.2 values were adopted for this study.

For Rb-90 and Sr-95, the mean energies in the JEF2.2 decay files were not taken from Rudstam although data for these nuclides are given in Reference [5]. The Rudstam values were adopted for this study.

The final values of mean gamma energy and the source of these values are given in Table 4.

5 FISPIN Calculations

The FISPIN code was used to perform fission pulse calculations for U-235 and Pu-239. The FISPIN executable was supplied by Nexia Solutions. The code version was FISPIN 10.2.1C.

The FISPIN input data for a U-235 fission pulse calculation was also supplied by Nexia Solutions. This case consisted of a single fission pulse followed by cooling from 0.1s to 1.0E9s with 10 time steps per decade. The input file is listed in Figure 1.

The calculations were run using the FISPIN fission product decay data library supplied by Nexia Solutions. This library was generated from JEFF3.1 evaluated decay data and uses thermal fission product yield data throughout.

For both U-235 and Pu-239, three variants of the fission pulse calculation were run. In the first, the data on the fission product decay library were unchanged giving results for the unmodified JEFF3.1 data. In the remaining two cases, the mean gamma decay energies for the fission products of interest were replaced by the values obtained from TAGS and from Rudstam/JEF2.2 respectively.

The mean gamma energies were updated using the OVERWRITE facility in FISPIN10. This has the form:

OVER 2 *nuclide* SGROUP 3 *value*

where *nuclide* is the nuclide name, ‘SGROUP 3’ indicates that the mean gamma decay energies are to be updated and *value* is the new value to be assigned, in MeV.

The input files used for the modified runs for U-235 are given in Figures 2 and 3.

The total gamma energies from the decay of fission products, at each time step, for each of the six calculations are listed in Table 5. The results for U-235 and Pu-239 were compared with experimental values and are discussed in the following section. As this study is concerned with short lived nuclides, results are presented up to 10,000 seconds only. After this time, there are no significant differences between the results from the three variants of the cases.

6 Analysis

For U-235 and Pu-239, three calculations were performed. These were a base calculation using unmodified JEFF3.1 fission product decay data and two further calculations in which the mean gamma energies for the nuclides of interest were replaced by those from TAGS and from Rudstam/JEF2.2. Henceforth, these calculations are referred to as JEFF3.1, TAGS and Rudstam respectively.

In Figures 4 and 5, the JEFF3.1, TAGS and Rudstam values for the gamma energies from the decay of fission products for U-235 and Pu-239 respectively are compared with the values from Tobias (see Section 2).

The JEFF3.1 results show that, for both U-235 and Pu-239, the gamma decay energies are significantly under-predicted for all cooling times up to ~3000s.

The results for Rudstam provide an indication of the variation in total gamma decay energies due to the application of measured mean gamma energy values prior to the availability of the TAGS data. These results indicate that, for both U-235 and Pu-239, the application of the Rudstam data does not lead to any improvement over JEFF3.1.

For U-235, the TAGS results show an improvement, relative to JEFF3.1, for all times up to ~3000s. This improvement is particularly marked over the important range of maximum decay energy between 20 and 200s. However, relative to Tobias, the TAGS results under-predict decay heat. The under-prediction is most significant in the ranges 1s – 100s and 400s – 3000s where the under-prediction is approximately 7 – 14%. Between 100s and 400s there is a smaller under-prediction whilst above 3000s the results are within Tobias' quoted uncertainties.

For Pu-239, the TAGS results again show a significant improvement over JEFF3.1 particularly over the range of maximum decay energy. Relative to Tobias, the TAGS results show an under-prediction of up to ~14% in the ranges 10s – 50s and 300s – 4000s. Elsewhere, the results are within the uncertainties.

In order to compare the results with studies carried out for WPEC Sub-group 25 [10], Figures 6 and 7 include experimental data from the University of Tokyo[12], Oak Ridge National Laboratory[13] and University of Massachusetts Lowell [15], taken from Yoshida's graphs [18]. Calculations for Sub-group 25, carried out to date, have been compared with these measurements rather than with Tobias' evaluation.

Comparison with these three sets of measurements shows that the U-235 TAGS results are slightly low from 1 - ~20s but are in agreement with the modern experiments above this.

For Pu-239, the TAGS results under-predict the decay heat by a small amount between 10 and 30s and more significantly between 400s and 6000s {interestingly, if JEF-2.2 data are enhanced with TAGS mean energies the fit is very good in this region [4]}. Elsewhere, the TAGS values are within experimental error.

It is noted that all the calculations in this study use thermal fission product yields and that the results compare almost exactly with results for JEFF3.1 and JEFF3.1 plus TAGS , presented by Yoshida [18] to Sub-group 25. Yosida's results for U-235 include data for JENDL and JENDL plus TAGS mean gamma energies. These indicate that, over the important range of peak gamma energy from ~20s to ~300s, the results for JEFF3.1 plus TAGS are in better agreement with the experimental data than JENDL plus TAGS which overestimate the decay heat in this range. However. if Tobias' evaluation is considered as the reference, then the JENDL TAGS data seem a better fit than those adjusted from JEFF3.1.

7 Conclusions

Calculations of gamma energy from the decay of fission products following fission bursts in U-235 and Pu-239 have been performed using FISPIN 10. The effects of replacing the JEFF3.1 mean gamma decay energies, for short lived isotopes of Rb, Sr, Y, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, and Eu, by the values obtained from TAGS and from Rudstam/JEF2.2 were studied. Thermal fission product yield data were used throughout.

The calculations have been compared with Tobias' evaluation of experimental data and with three sets of measured data.

The results using the Rudstam/JEF2.2 mean gamma energies show no improvement over the unmodified JEFF3.1 data.

The results using the TAGS mean gamma energies show a significant improvement, relative to JEFF3.1, for both U-235 and Pu-239. The improvement is particularly marked over the range of peak gamma energy from ~20s to 200s. Overall, there is still a tendency for the calculations to under-predict decay heat relative to experiment. This is most notable for Pu-239 between 300s and 4000s.

For U-235, Tobias' data are generally higher than the experimental data up to ~100s. Considering work done by Yoshida for WPEC Sub-group 25, JENDL data incorporating the TAGS mean gamma energies would seem to give better agreement with Tobias than JEFF3.1 plus TAGS.

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Table 3. Mean Gamma Energies from TAGS

Nuclide	Mean Gamma Energy (keV)				E_{conv}	TAGS-E_{conv}	TAGS/ JEFF3.1	TAGS/ENSDF
	JEFF3.1	JEFF3.1 Evaluation	ENSDF	TAGS				
Ba-141	868.5324	ENSDF	875.8791	906.3956	17.95	888.4456	1.02	1.01
Ba-142	1038.6301	ENSDF	1102.6885	1059.6882	22.4975	1037.1907	1.00	0.94
Ba-143	-	NUBASE	1055.2203	1249.8541	0	1249.8541	-	1.18
Ba-144	-	NUBASE	613.0803	762.8432	0	762.8432	-	1.24
Ba-145	-	NUBASE	337.1133	1832.9019	0	1832.9019	-	5.44
Ce-145	584.5079	NICHOLS	836.6565	883.5335	36.4552	847.0783	1.45	1.01
Ce-146	-	NUBASE	356.2390	352.6918	0	352.6918	-	0.99
Ce-147	165.4936	NICHOLS	177.9082	1496.5740	15.7107	1480.8633	8.95	8.32
Ce-148	-	NUBASE	357.6081	485.7978	0	485.7978	-	1.36
Cs-138g	2354.5288	ENSDF	2364.1667	2407.8291	5.4407	2402.3884	1.02	1.02
Cs-138m	-	NUBASE	2149.0154	2241.0027	0	2241.0027	-	1.04
Cs-139	344.5597	ENSDF	339.8411	304.8605	0	304.8605	0.88	0.90
Cs-140	1675.3424	ENSDF	1604.1267	1941.6343	2.1916	1939.4427	1.16	1.21
Cs-141	752.6038	ENSDF	776.9636	1701.3070	18.3584	1682.9486	2.24	2.17
Eu-158	1261.0224	ENSDF	1100.7128	1368.6543	37.5943	1331.0600	1.06	1.21
La-142	2324.6017	ENSDF	2312.5447	2121.1802	1.9827	2119.1975	0.91	0.92
La-143	252.2913	ENSDF	265.4304	439.4180	0	439.4180	1.74	1.66
La-144	2329.1945	ENSDF	2303.7041	3085.0029	9.8117	3075.1912	1.32	1.33
La-145	606.9521	ENSDF	625.4421	2098.8003	23.8555	2074.9448	3.42	3.32
Nd-149	356.9377	ENSDF	411.8346	401.8708	42.6758	359.1950	1.01	0.87
Nd-151	835.3047	ENSDF	998.4231	900.8771	19.4316	881.4455	1.06	0.88
Nd-153	-	NUBASE	453.5189	508.6399	0	508.6399	-	1.12
Nd-154	-	NUBASE	522.8065	550.6107	0	550.6107	-	1.05
Nd-155	-	NUBASE	1040.6729	1542.8800	0	1542.8800	-	1.48
Pm-152	280.8396	ENSDF	289.2105	345.4300	17.607	327.8230	1.17	1.13
Pm-153	70.8683	ENSDF	98.1654	122.5544	10.496	112.0584	1.58	1.14

Nuclide	Mean Gamma Energy (keV)				E_{conv}	TAGS-E_{conv}	TAGS/ JEFF3.1	TAGS/ENSDF
	JEFF3.1	JEFF3.1 Evaluation	ENSDF	TAGS				
Pm-154	-	NUBASE	1836.7985	1875.9275	0	1875.9275	-	1.02
Pm-155	119.9459	ENSDF	472.9546	563.6347	2.2239	561.4108	4.68	1.19
Pm-156	-	NUBASE	1878.6512	2205.5891	0	2205.5891	-	1.17
Pm-157	-	NUBASE	529.9091	849.0458	0	849.0458	-	1.60
Pr-146	987.4145	ENSDF	976.0142	1054.5431	0	1054.5431	1.07	1.08
Pr-147	-	NUBASE	686.9684	742.7675	0	742.7675	-	1.08
Pr-148 (2.0 s)	936.7959	ENSDF	983.2078	2049.5840	8.7768	2040.8072	2.18	2.08
Pr-148 (2.27s)	936.7959	ENSDF	763.8909	1776.4341	8.7768	1767.6573	1.89	2.31
Pr-149	296.6472	ENSDF	340.5189	1332.0061	30.8056	1301.2005	4.39	3.82
Pr-151	-	NUBASE	453.4236	1362.4554	0	1362.4554	-	3.00
Rb-89	2231.2065	NICHOLS	2012.0309	2229.3252	0.6915	2228.6337	1.00	1.11
Rb-90	1981.8857	ENSDF	1394.1700	2270.5908	0	2270.5908	1.15	1.63
Rb-90m	3240.2076	ENSDF	3258.1074	3969.1096	0.6713	3968.4383	1.22	1.22
Rb-91	2265.7871	ENSDF	2325.7827	2706.3806	34.2983	2672.0823	1.18	1.15
Rb-93	2593.1633	NICHOLS	1944.1582	2561.4106	1.619	2559.7916	0.99	1.32
Sm-157	-	NUBASE	437.8761	583.3181	0	583.3181	-	1.33
Sm-158	-	NUBASE	500.1192	590.3376	0	590.3376	-	1.18
Sr-93	2216.7973	ENSDF	2207.3533	2167.5037	26.5031	2141.0006	0.97	0.97
Sr-94	1424.8582	NICHOLS	1416.2294	1419.2402	0.2596	1418.9806	1.00	1.00
Sr-95	1118.0956	ENSDF	1123.5894	1789.6865	0.0835	1789.6030	1.60	1.59
Y-94	764.231	ENSDF	767.3026	757.0031	0	757.0031	0.99	0.99
Y-95	1091.9541	ENSDF	1094.2644	1222.4224	0	1222.4224	1.12	1.12

Table 4. Mean Gamma Energies from Rudstam/JEF2.2

Nuclide	JEF2.2 E_γ (keV)	unc.	Rudstam E_γ (keV)	unc.	Rudstam /JEFF2.2	Selected E_γ (keV)	Unc.	Source	JEFF3.1 E_γ (keV)	Selected/ JEFF3.1
Ba-141	965.644	12.875	620.0	40.0	0.64	965.644	12.875	Rudstam/JEF2.2	868.5324	1.11
Ba-142	760.000	80.000	760.0	80.0	1.00	760.000	80.000	Rudstam/JEF2.2	1038.6300	0.73
Ba-143	870.000	100.000	870.0	100.0	1.00	870.000	100.000	Rudstam/JEF2.2	(nubase)	
Ba-144	480.000	50.000	480.0	50.0	1.00	480.000	50.000	Rudstam/JEF2.2	(nubase)	
Ba-145	422.000	19.000	1460.0	130.0	3.46	422.000	19.000	Rudstam/JEF2.2	(nubase)	
Ce-145	770.000	70.000	770.0	70.0	1.00	770.000	70.000	Rudstam/JEF2.2	584.5079	1.32
Ce-146	180.000	15.000	-			180.000	15.000	Rudstam/JEF2.2	(nubase)	
Ce-147	620.000	110.000	620.0	110.0	1.00	620.000	110.000	Rudstam/JEF2.2	165.4936	3.75
Ce-148	303.000	6.000	-			303.000	6.000	JEF2.2	(nubase)	
Cs-138	2361.100	29.832	-			2361.100	29.832	JEF2.2	2354.5290	1.00
Cs-138m	420.000	50.000	500.0	80.0		420.000	50.000	Rudstam/JEF2.2	(nubase)	
Cs-139	299.000	21.000	299.0	21.0	1.00	299.000	21.000	Rudstam/JEF2.2	344.5597	0.87
Cs-140	1590.000	40.000	1270.0	50.0	0.80	1590.000	40.000	Rudstam/JEF2.2	1675.3420	0.95
Cs-141	1140.000	90.000	1140.0	90.0	1.00	1140.000	90.000	Rudstam/JEF2.2	752.6038	1.51
Eu-158	1084.000	13.000	-			1084.000	13.000	JEF2.2	1261.0220	0.86
La-142	2368.000	16.000	-			2368.000	16.000	JEF2.2	2324.6020	1.02
La-143	130.000	40.000	130.0	40.0	1.00	130.000	40.000	Rudstam/JEF2.2	252.2913	0.52
La-144	2240.000	230.000	2240.0	230.0	1.00	2240.000	230.000	Rudstam/JEF2.2	2329.1950	0.96
La-145	1480.000	80.000	1480.0	80.0	1.00	1480.000	80.000	Rudstam/JEF2.2	606.9521	2.44
Nd-149	371.000	6.000	-			371.000	6.000	JEF2.2	356.9377	1.04
Nd-151	946.000	13.000	-			946.000	13.000	JEF2.2	835.3047	1.13
Nd-153	93.000	18.600	-			93.000	18.600	JEF2.2	(nubase)	
Nd-154	396.000	79.200	-			396.000	79.200	JEF2.2	(nubase)	
Nd-155	2308.000	461.600	-			2308.000	461.600	JEF2.2	(nubase)	
Pm-152	150.140	7.560	-			150.140	7.560	JEF2.2	280.8396	0.53
Pm-153	53.666	1.499	-			53.666	1.499	JEF2.2	70.8683	0.76

Nuclide	JEF2.2 E_γ (keV)	unc.	Rudstam E_γ (keV)	unc.	Rudstam /JEFF2.2	Selected E_γ (keV)	Unc.	Source	JEFF3.1 E_γ (keV)	Selected/ JEFF3.1
Pm-154	1792.490	277.555	-			1792.490	277.555	JEF2.2	(nubase)	
Pm-155	296.000	59.200	-			296.000	59.200	JEF2.2	119.9459	2.47
Pm-156	2215.000	443.000	-			2215.000	443.000	JEF2.2	(nubase)	
Pm-157	477.000	95.400	-			477.000	95.400	JEF2.2	(nubase)	
Pr-146	1010.000	21.000	-			1010.000	21.000	JEF2.2	987.4145	1.02
Pr-147	840.000	190.000	840.0	190.0	1.00	840.000	190.000	Rudstam/JEF2.2	(nubase)	
Pr-148	715.809	13.747	-			715.809	13.747	JEF2.2	936.7959	0.76
Pr-149	417.831	13.588	-			417.831	13.588	JEF2.2	296.6472	1.41
Pr-151	655.000	131.000	-			655.000	131.000	JEF2.2	(nubase)	
Rb-89	1740.000	40.000	1740.0	40.0	1.00	1740.000	40.000	Rudstam/JEF2.2	2231.2070	0.78
Rb-90	2171.940	24.179	1710.0	50.0	0.79	1710.0	50.0	Rudstam	1981.8860	0.86
Rb-90m	3690.000	110.000	3690.0	110.0	1.00	3690.000	110.000	Rudstam/JEF2.2	3240.2080	1.14
Rb-91	2335.000	33.000	2335.0	33.0	1.00	2335.000	33.000	Rudstam/JEF2.2	2265.7870	1.03
Rb-93	1920.000	100.000	1920.0	100.0	1.00	1920.000	100.000	Rudstam/JEF2.2	2593.1630	0.74
Sm-157	532.000	23.000	-			532.000	23.000	JEF2.2	(nubase)	
Sm-158	330.000	66.000	-			330.000	66.000	JEF2.2	(nubase)	
Sr-93	1760.000	70.000	1760.0	70.0	1.00	1760.000	70.000	Rudstam/JEF2.2	2216.7970	0.79
Sr-94	1450.000	10.000	1450.0	10.0	1.00	1450.000	10.000	Rudstam/JEF2.2	1424.8580	1.02
Sr-95	1341.400	16.510	1180.0	100.0	0.88	1180.0	100.0	Rudstam	1118.0960	1.06
Y-94	900.000	50.000	900.0	50.0	1.00	900.000	50.000	Rudstam/JEF2.2	764.2310	1.18
Y-95	1060.000	120.000	1060.0	120.0	1.00	1060.000	120.000	Rudstam/JEF2.2	1091.9540	0.97

Table 5. Gamma Energies from the Decay of Fission Products

Time (s)	U-235				Pu-239		
	JEFF3.1	TAGS	Rudstam-JEF2.2		JEFF3.1	TAGS	Rudstam-JEF2.2
1.0E-01	5.34419E-01	5.36034E-01	5.25317E-01		3.93687E-01	3.95538E-01	3.89533E-01
2.0E-01	4.84135E-01	4.85797E-01	4.75105E-01		3.56904E-01	3.58771E-01	3.52791E-01
3.0E-01	4.44909E-01	4.46613E-01	4.35952E-01		3.28635E-01	3.30517E-01	3.24562E-01
4.0E-01	4.13302E-01	4.15046E-01	4.04421E-01		3.06079E-01	3.07976E-01	3.02048E-01
5.0E-01	3.87092E-01	3.88873E-01	3.78289E-01		2.87470E-01	2.89379E-01	2.83479E-01
6.0E-01	3.64822E-01	3.66639E-01	3.56098E-01		2.71666E-01	2.73588E-01	2.67717E-01
7.0E-01	3.45513E-01	3.47363E-01	3.36869E-01		2.57925E-01	2.59858E-01	2.54017E-01
8.0E-01	3.28493E-01	3.30375E-01	3.19931E-01		2.45749E-01	2.47694E-01	2.41883E-01
9.0E-01	3.13293E-01	3.15205E-01	3.04813E-01		2.34803E-01	2.36758E-01	2.30979E-01
1.0E+00	2.99573E-01	3.01515E-01	2.91177E-01		2.24851E-01	2.26815E-01	2.21067E-01
2.0E+00	2.08729E-01	2.10919E-01	2.01186E-01		1.56861E-01	1.58906E-01	1.53481E-01
3.0E+00	1.58703E-01	1.61088E-01	1.51989E-01		1.18229E-01	1.20334E-01	1.15224E-01
4.0E+00	1.26820E-01	1.29362E-01	1.20874E-01		9.35708E-02	9.57224E-02	9.09079E-02
5.0E+00	1.04907E-01	1.07577E-01	9.96557E-02		7.67742E-02	7.89599E-02	7.44172E-02
6.0E+00	8.90670E-02	9.18391E-02	8.44363E-02		6.47766E-02	6.69865E-02	6.26920E-02
7.0E+00	7.71726E-02	8.00257E-02	7.30924E-02		5.58778E-02	5.81035E-02	5.40348E-02
8.0E+00	6.79680E-02	7.08842E-02	6.43743E-02		4.90697E-02	5.13042E-02	4.74404E-02
9.0E+00	6.06683E-02	6.36322E-02	5.75031E-02		4.37245E-02	4.59617E-02	4.22841E-02
1.0E+01	5.47594E-02	5.77581E-02	5.19715E-02		3.94347E-02	4.16695E-02	3.81611E-02
2.0E+01	2.79778E-02	3.09192E-02	2.71945E-02		2.03649E-02	2.24198E-02	1.99980E-02
3.0E+01	1.91885E-02	2.17961E-02	1.89999E-02		1.41522E-02	1.59345E-02	1.40701E-02
4.0E+01	1.47709E-02	1.70106E-02	1.47701E-02		1.09931E-02	1.25108E-02	1.10056E-02
5.0E+01	1.20364E-02	1.39384E-02	1.20895E-02		9.01262E-03	1.02981E-02	9.05299E-03
6.0E+01	1.01327E-02	1.17431E-02	1.01906E-02		7.61778E-03	8.70702E-03	7.66025E-03
7.0E+01	8.71184E-03	1.00771E-02	8.75645E-03		6.56602E-03	7.49224E-03	6.60064E-03

Time (s)	U-235				Pu-239		
	JEFF3.1	TAGS	Rudstam-JEF2.2		JEFF3.1	TAGS	Rudstam-JEF2.2
8.0E+01	7.60369E-03	8.76550E-03	7.62947E-03		5.73901E-03	6.53088E-03	5.76261E-03
9.0E+01	6.71345E-03	7.70748E-03	6.72024E-03		5.07070E-03	5.75213E-03	5.08313E-03
1.0E+02	5.98286E-03	6.83871E-03	5.97271E-03		4.52028E-03	5.11089E-03	4.52267E-03
2.0E+02	2.58582E-03	2.85939E-03	2.51956E-03		1.97715E-03	2.18077E-03	1.94403E-03
3.0E+02	1.55932E-03	1.69306E-03	1.49793E-03		1.23330E-03	1.33782E-03	1.20078E-03
4.0E+02	1.12376E-03	1.20236E-03	1.07009E-03		9.20051E-04	9.82687E-04	8.90639E-04
5.0E+02	8.92271E-04	9.42847E-04	8.45197E-04		7.51544E-04	7.91949E-04	7.25180E-04
6.0E+02	7.48038E-04	7.82400E-04	7.06494E-04		6.44311E-04	6.71606E-04	6.20739E-04
7.0E+02	6.48136E-04	6.72432E-04	6.11297E-04		5.68083E-04	5.87206E-04	5.47037E-04
8.0E+02	5.73974E-04	5.91751E-04	5.41203E-04		5.09890E-04	5.23744E-04	4.91122E-04
9.0E+02	5.16264E-04	5.29692E-04	4.87054E-04		4.63335E-04	4.73706E-04	4.46621E-04
1.0E+03	4.69794E-04	4.80248E-04	4.43728E-04		4.24877E-04	4.32892E-04	4.10010E-04
2.0E+03	2.46977E-04	2.49363E-04	2.38575E-04		2.27188E-04	2.29024E-04	2.22850E-04
3.0E+03	1.61624E-04	1.62446E-04	1.58977E-04		1.46826E-04	1.47466E-04	1.45739E-04
4.0E+03	1.16687E-04	1.16826E-04	1.15950E-04		1.03904E-04	1.04008E-04	1.03780E-04
5.0E+03	8.94908E-05	8.93057E-05	8.93932E-05		7.79863E-05	7.78311E-05	7.81242E-05
6.0E+03	7.14582E-05	7.11225E-05	7.15632E-05		6.10416E-05	6.07642E-05	6.12278E-05
7.0E+03	5.86946E-05	5.82969E-05	5.88499E-05		4.92962E-05	4.89676E-05	4.94699E-05
8.0E+03	4.92146E-05	4.88013E-05	4.93688E-05		4.07757E-05	4.04338E-05	4.09240E-05
9.0E+03	4.19161E-05	4.15121E-05	4.20541E-05		3.43684E-05	3.40337E-05	3.44921E-05
1.0E+04	3.61445E-05	3.57627E-05	3.62640E-05		2.94113E-05	2.90947E-05	2.95146E-05

Figure 1. FISPIN Input Data for Unmodified U-235 Fission Pulse

```
NOINT
NOLIB
TAPE 3
FISPIN
* JEFF3.1, Decay Heat from a U235 fission pulse.
* NDATA/05-06/2/gen/13- Decay heat calculations.
* Single fission pulse with 1-1E9 second coolings.
* Gamma energies all from JEFF3.1
* ---------------------------------------------------
PRINTLIB
NEWOUT 0
INTE
MILL MILA
NSPEC .333 .333 .333
LEVEL 200 1
FFRAC 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
FRATE   1.0E10
TIME    1E-10
ATOMS
TABQ 36
FRATE   0.0
TIME    0.1 ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME    1         ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME         10   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME        100   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME       1000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME      10000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME     100000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME    1000000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME   10000000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME  100000000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
END
```

Figure 2. FISPIN Input Data with TAGS Mean Gamma Energies

```
NOINT
NOLIB
TAPE 3
FISPIN
* 02598fp05ne, Decay Heat from a U235T fission pulse.
* NDATA/05-06/2/gen/13- Decay heat calculations.
* Single fission pulse with 1-1E9 second coolings.
* -----------------------------------------------------
* Set Gamma decay energy release to Rudstam/JEF2.2 values
*----------------------------------------------------
OVER 2 BA141 SGROUP 3 0.906396
OVER 2 BA142 SGROUP 3 1.05969
OVER 2 BA143 SGROUP 3 1.24985
OVER 2 BA144 SGROUP 3 0.762843
OVER 2 BA145 SGROUP 3 1.8329
OVER 2 CE145 SGROUP 3 0.883533
OVER 2 CE146 SGROUP 3 0.352692
OVER 2 CE147 SGROUP 3 1.49657
OVER 2 CE148 SGROUP 3 0.485798
OVER 2 CS138 SGROUP 3 2.40783
OVER 2 CS138M SGROUP 3 2.241
OVER 2 CS139 SGROUP 3 0.30486
OVER 2 CS140 SGROUP 3 1.94163
OVER 2 CS141 SGROUP 3 1.70131
OVER 2 EU158 SGROUP 3 1.36865
OVER 2 LA142 SGROUP 3 2.12118
OVER 2 LA143 SGROUP 3 0.439418
OVER 2 LA144 SGROUP 3 3.085
OVER 2 LA145 SGROUP 3 2.0988
OVER 2 ND149 SGROUP 3 0.401871
OVER 2 ND151 SGROUP 3 0.900877
OVER 2 ND153 SGROUP 3 0.50864
OVER 2 ND154 SGROUP 3 0.550611
OVER 2 ND155 SGROUP 3 1.54288
OVER 2 PM152 SGROUP 3 0.34543
OVER 2 PM153 SGROUP 3 0.122554
OVER 2 PM154 SGROUP 3 1.87593
OVER 2 PM155 SGROUP 3 0.563635
OVER 2 PM156 SGROUP 3 2.20559
OVER 2 PM157 SGROUP 3 0.849046
OVER 2 PR146 SGROUP 3 1.05454
OVER 2 PR147 SGROUP 3 0.742768
OVER 2 PR148 SGROUP 3 2.04958
OVER 2 PR149 SGROUP 3 1.33201
OVER 2 PR151 SGROUP 3 1.36246
OVER 2 RB89 SGROUP 3 2.22933
OVER 2 RB90 SGROUP 3 2.27059
OVER 2 RB90M SGROUP 3 3.96911
OVER 2 RB91 SGROUP 3 2.70638
OVER 2 RB93 SGROUP 3 2.56141
OVER 2 SM157 SGROUP 3 0.583318
OVER 2 SM158 SGROUP 3 0.590338
OVER 2 SR93 SGROUP 3 2.1675
OVER 2 SR94 SGROUP 3 1.41924
OVER 2 SR95 SGROUP 3 1.78969
OVER 2 Y94 SGROUP 3 0.757003
```

```
OVER 2 Y95 SGROUP 3 1.22242
PRINTLIB
NEWOUT 0
INTE
MILL MILA
NSPEC .333 .333 .333
LEVEL 200 1
FFRAC 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
FRATE   1.0E10
TIME    1E-10
ATOMS
TABQ 36
FRATE   0.0
TIME    0.1 ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME    1         ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME          10   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME         100   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME        1000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME       10000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME      100000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME     1000000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME    10000000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
TIME   100000000   ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS ATOMS
END
```

Figure 3. FISPIN Input Data with Rudstam/JEF2.2 Mean Gamma Energies

```
NOINT
NOLIB
TAPE 3
FISPIN
* 02598fp05ne, Decay Heat from a U235T fission pulse.
* NDATA/05-06/2/gen/13- Decay heat calculations.
* Single fission pulse with 1-1E9 second coolings.
* ----------------------------------------------------
* Set Gamma decay energy release to Rudstam/JEF2.2 values
*----------------------------------------------------
OVER 2 BA141 SGROUP 3 0.965644
OVER 2 BA142 SGROUP 3 0.76
OVER 2 BA143 SGROUP 3 0.87
OVER 2 BA144 SGROUP 3 0.48
OVER 2 BA145 SGROUP 3 0.422
OVER 2 CE145 SGROUP 3 0.77
OVER 2 CE146 SGROUP 3 0.18
OVER 2 CE147 SGROUP 3 0.62
OVER 2 CE148 SGROUP 3 0.303
OVER 2 CS138 SGROUP 3 2.3611
OVER 2 CS138M SGROUP 3 0.42
OVER 2 CS139 SGROUP 3 0.299
OVER 2 CS140 SGROUP 3 1.59
OVER 2 CS141 SGROUP 3 1.14
OVER 2 EU158 SGROUP 3 1.084
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OVER 2 RB93 SGROUP 3 1.92
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Figure 4. U-235 Gamma Energy from Fission Product Decay

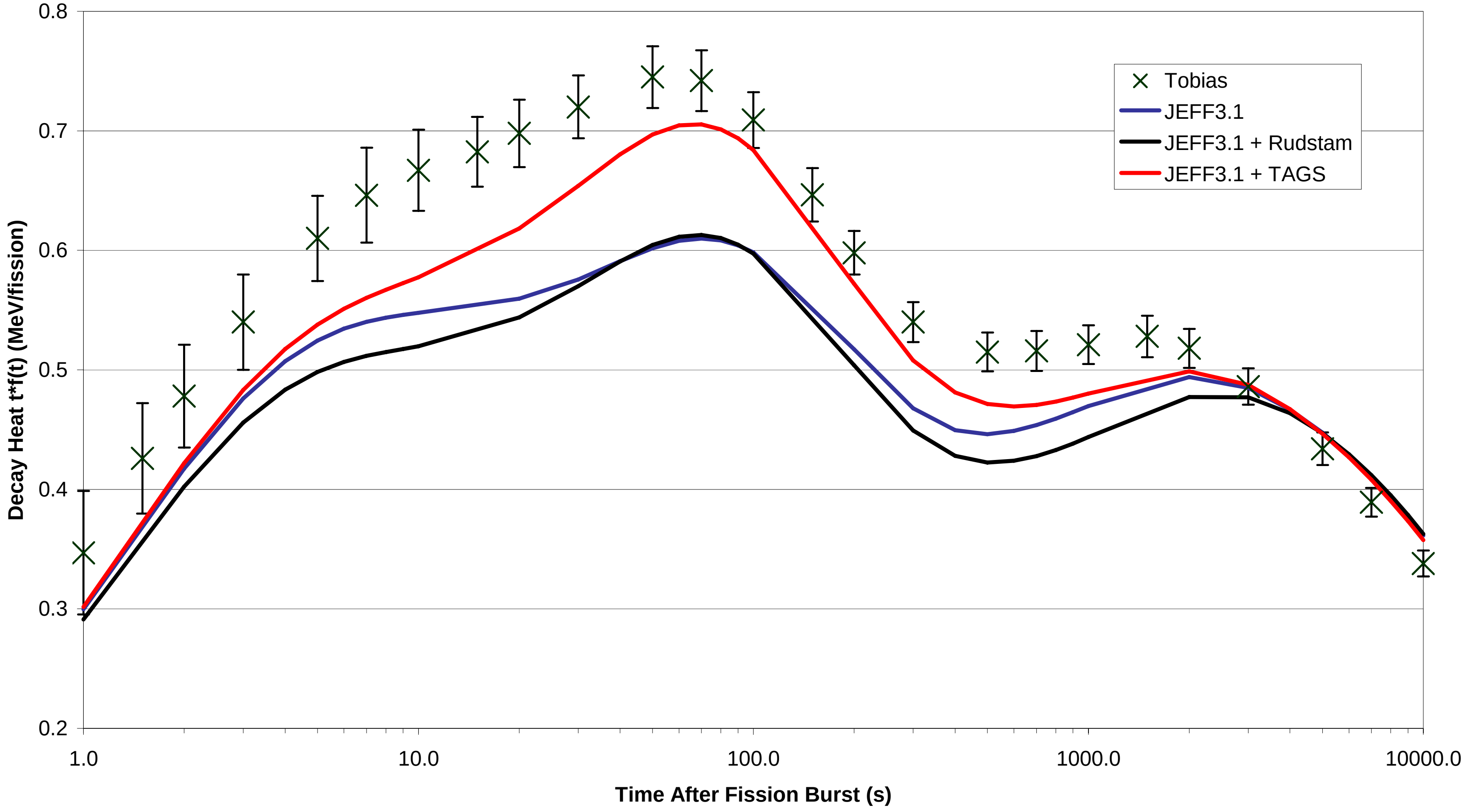


Figure 5. Pu-239 Gamma Energy from Fission Product Decay

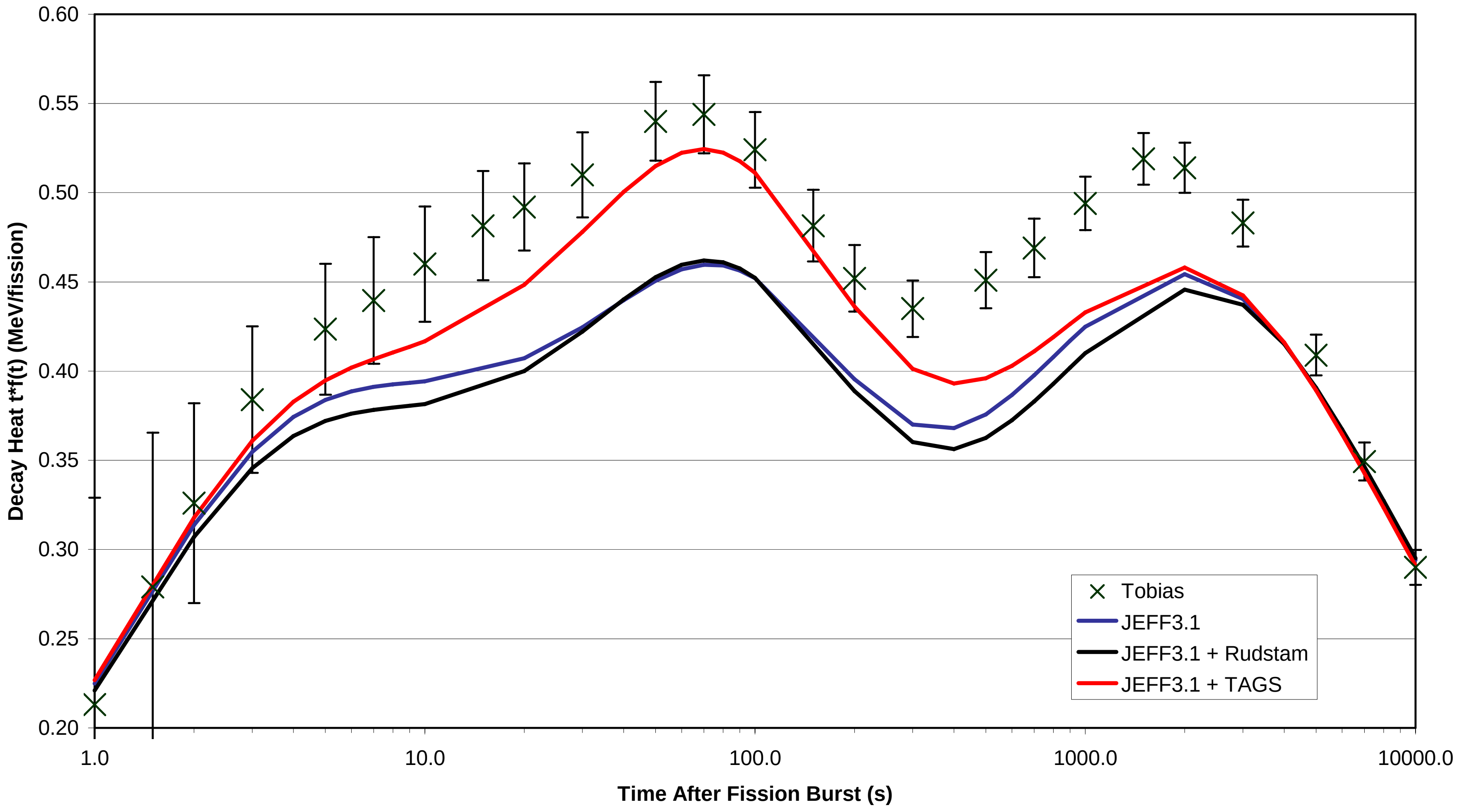


Figure 6. U-235 Gamma Energy Comparison with Experiment

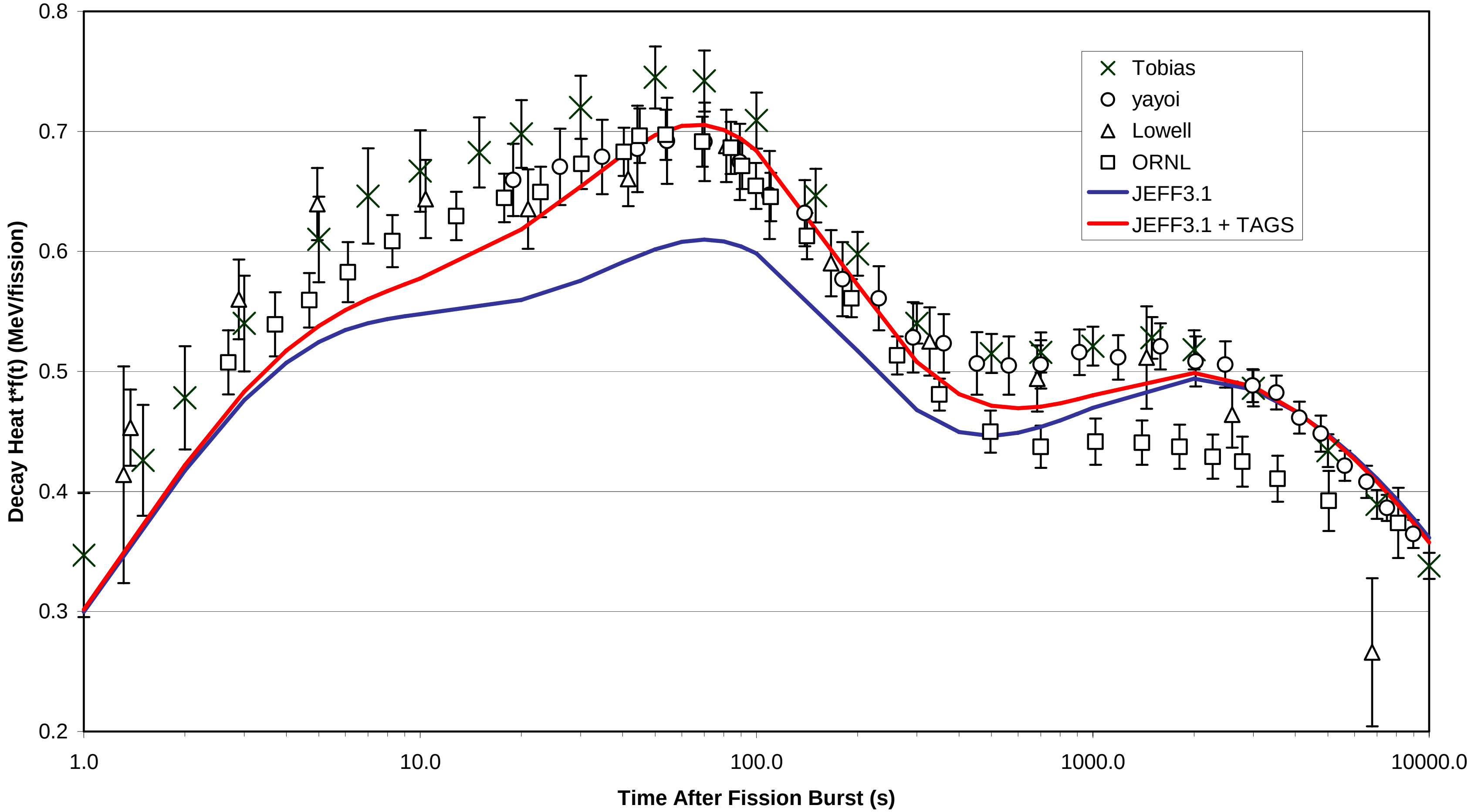
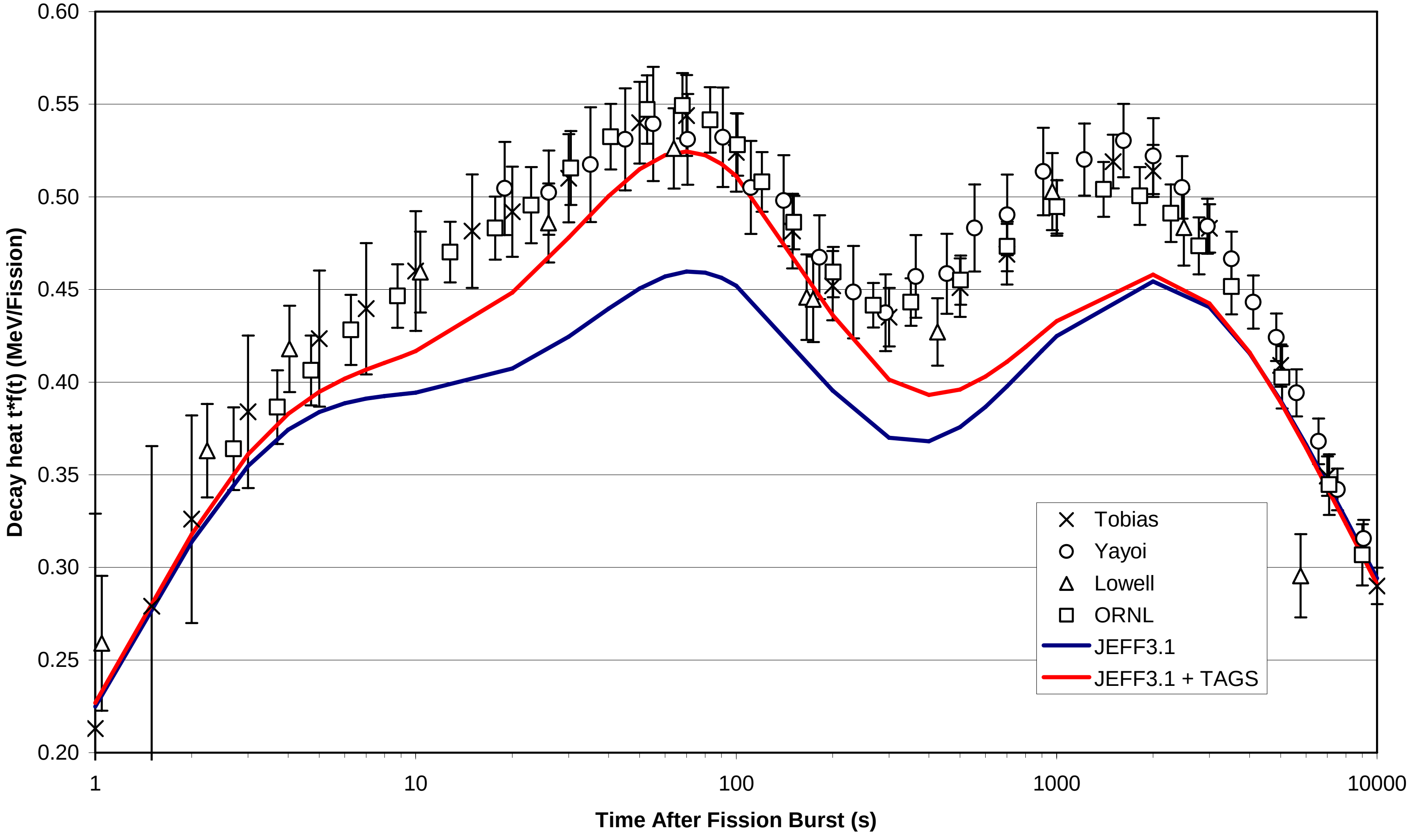


Figure 7. Pu-239 Gamma Energy Comparison with Experiment



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