



Nuclear data evaluation for decay heat analysis of spent nuclear fuel over 1–100 k year timescale

Hannah R. Doran^{1,2,a} , Alan J. Cresswell² , David C. W. Sanderson² , Gioia Falcone¹ 

¹ James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

² Scottish Universities Environmental Research Centre, East Kilbride G75 0QF, UK

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Abstract Accurate nuclear data are essential in the evaluation of decay heat from spent nuclear fuel (SNF). The accuracy of such data was assessed using an approach that compares values reported in different evaluated libraries and determines whether discrepancies reflect inaccuracies in primary data. A short list of 43 isotopes which are most significant to SNF decay heat calculations over 1–100 k years was produced by combining generic reactor inventory code with decay heat analysis for undifferentiated SNF. Decay properties (half-lives and decay energies) and neutron interactions (cross section and fission yields) were compared from 6 evaluated libraries. Fission product (FP) discrepancies identified are 90Sr half-life, where inclusion of a single measurement significantly reduces the evaluated value; 95mNb beta energy, where DDEP evaluation omits the decay to the 95Mo ground state; 99Tc beta energy, where evaluations differ by approximately 10% with a variety of shape factors used; 126Sb/126mSb beta (JEF2.2/3.1.1/3.3) and electron energies (JEFF3.1.1), where intensity differences are reported; and 137Cs beta energy, where ENDF/B-VIII.0 and JEF3.3 evaluations use incorrect shape factors. For actinides, the major discrepancies identified were 237Np alpha energy (JEF2.2/3.1.1) and 225Ac electron energies (ENDF/B-VIII.0) but overall show less discrepancies during long-term disposal (0.1–100 ky) compared to FP's during interim storage (1–100 years). Further assessments of the 90Sr half-life and the best shape factor for the 99Tc beta decay are needed to improve future decay heat analyses, which are important for designing future stores and evaluating schemes for possible heat recovery.

1 Introduction

In specific circumstances, confidence in the precision and accuracy of nuclear data is critical to develop reactor models and understand the curation of radioactive wastes over long timescales. Unsurprisingly, modeling decay heat from spent nuclear fuel (SNF) may be considered essential to underpin safe storage and disposal of radioactive waste. In addition, the possibility that heat generated by radioactive waste could be recoverable to offset carbon costs associated with long-term management also requires accurate decay heat models. In both cases, it is important to assess nuclear data confidence levels. For decay heat modeling, the half-lives, decay energies and intensities are the quantities requiring assessment, where modeling of SNF includes the calculation of inventories produced during and after reactor operation then fission yields and neutron capture cross sections are also required.

Previous studies have propagated uncertainties in nuclear data from single evaluated libraries through decay heat analyses. A so-called pandemonium effect was identified in key fission product (FP) decay heat contributors during pre- and post-reactor operating times [1, 2]. These systematic errors cause an underestimate in total gamma-ray energies and an overestimate in total beta energies [2] when a high-resolution germanium detector is used for data measurements. Propagation errors were also identified in FP gamma emissions for short cooling times (< 1 year) [3], fission yield data for long cooling times (< 1000 years) and cross-sectional data for longer cooling times (> 1000 years) [4]. These decay heat uncertainties were identified for a single library—ENDF/B-VII.1—by adopting a Monte Carlo Sampling Method [3, 4], recognizing the importance of improved precision in decay heat calculations, especially for long term modeling. Comparisons of different libraries has identified significant variability for natural radionuclide decay data [5].

The work reported here applies the methodology of [5, 6] to FP and actinides, comparing nuclear data in different evaluated libraries to identify where discordance between them might reflect issues with the primary data that would not be evident if only one library was used. In this work a simulation of typical SNF is used to identify those nuclides which are significant in contributing to the total decay heat at different stages of post-irradiation decay. For this manageable subset of the nuclides present in SNF, relevant nuclear data have been tabulated from six different evaluated libraries, any discrepancies noted and the nuclear data contributing to those discrepancies examined in more detail. It is not the intention of this work to produce comprehensive re-appraisals of existing

^a e-mail: h.doran.1@research.gla.ac.uk (corresponding author)

data, rather to identify nuclides where inconsistencies lead to reduced confidence in evaluated data, and for those where this is significant for decay heat evaluation briefly discuss the data and suggest further work that could address issues identified.

2 Methods

2.1 Identification of radionuclides for further investigation

A simulation code developed and validated for modeling the irradiation of ^{235}U with thermal neutrons [7,8], modified to approximate fast neutron interactions and actinide production, was used to simulate a typical SNF inventory and model the decay over 100k years. For this purpose, the fuel was 1t of natural uranium with an irradiation period (1934 d or 5.3 y) and power output (3.62 MWth) typical of Magnox reactors. Other fuel and thermal reactor types will produce slightly different inventories, but the radionuclides contributing to the majority of the total decay heat are not expected to vary significantly. Inventory outputs were generated at different decay times (1, 5, 10, 50, 100, 500, 1 k, 5 k, 10 k, 50 k and 100 k years) to simulate an activity value per radionuclide. Mean energy values were obtained by considering the radiation energy and intensity data for each radionuclide. From this, a summation of the activity and mean energy values was performed to compute the decay heat produced by all radionuclides in the simulated fuel. The simulation code and the decay heat calculations use data from the JEF2.2 library [9]. For each time period a decay heat vs cooling time plot was generated, allowing the identification of nuclides that contribute 99% of the total heat at that decay time. Given the approximations in the simulation code, and the potential for different inventories of different fuels and reactor designs, any nuclide close to this threshold was also included in the list of nuclides of interest. This list was compared to other studies, and any other nuclides identified as significant decay heat contributors by other authors were also included in this analysis.

2.2 Nuclear data comparative assessment

For all the radionuclides identified as significant decay heat contributors, nuclear data were tabulated from six evaluated libraries. For this work, the nuclear data comprised of half-lives, mean decay energies, independent and cumulative fission yields and thermal neutron capture cross sections. The libraries interrogated were JEF2.2, JEFF3.1.1, JEFF3.3, ENDF/B-VIII.0, ENSDF and DDEP. Data from the first four of these were extracted using the JANIS 4.1 tool, ENSDF data were extracted using the NucDat 2.8 tool [10], and DDEP data were taken from LNHB [11]. For nuclides with short-lived decay products, the total energy is calculated including radiation from the decay products in equilibrium.

3 Results and discussion

3.1 Percentage decay heat contributors

Figure 1 illustrates a decay heat vs cooling time curve for one ton (1 t) of fuel on a log–log scale accompanied by a stacked percentage histogram in Fig. 2 displaying dominant radionuclides, across a cooling period 1–100 k years. There are 23 parent nuclides which contribute to 99% of the heat production at any time during the decay between 1 y and 100 ky and are plotted in Fig. 2. In green/turquoise, FP's such as ^{95}Zr , ^{106}Ru , ^{134}Cs , ^{137}Cs and ^{90}Sr dominate over 80% of the total decay heat for initial cooling times of 1–10 years, followed by ^{90}Sr and ^{137}Cs making up the bulk of FP heat up to 100 years. This FP list supports other literature, suggesting that FP's dominate the decay heat process during the interim storage and transportation period [3,12,13]. In particular, a similar investigation for light-water reactor (LWR) designs was proposed by [13], identifying all FP's highlighted in Fig. 2, also identifying ^{90}Y , ^{144}Pr , ^{137}mBa (which in this work have been included within the decay energy of their longer-lived parents). In orange/red, actinides such as ^{239}Pu , ^{240}Pu and ^{241}Am dominate the total decay heat percentage between cooling times 100–100 k years. In particular, the highest percentage seen are 98% for ^{239}Pu at 50 k years, 31% for ^{240}Pu at 5 k years and 40% for ^{241}Am at 500 years. This was also seen in [12] for PWR SNF at burnup 50 MWd/tHM, where the decay chains of ^{239}Pu , ^{240}Pu and ^{241}Am reach their maximum decay heat for these cooling times. Actinides ^{241}Pu , ^{242}Am and ^{244}Cm were also identified in [13] for total decay heat contributions of $\geq 99\%$ for a cooling period between 2 and 100 years. These additional nuclides which prior literature suggest are important have also been included within this analysis. Finally, nuclear data from an additional seventeen short-lived daughter products were added to the discrepancy analysis, assuming that these are in equilibrium with their corresponding parent nuclides identified in Fig. 2 and hence will pose some importance in decay heat contributions. In total, 43 nuclides were identified for further examination.

Fig. 1 Total decay heat versus cooling time (1–100 k years) for 1 t of fuel at constant thermal power 3.62 MW_{th} for 1934 days

Total Decay Heat (W/t) vs Cooling Time (years) on log-log scale for 1t Magnox fuel at 3.62 MW_{th}

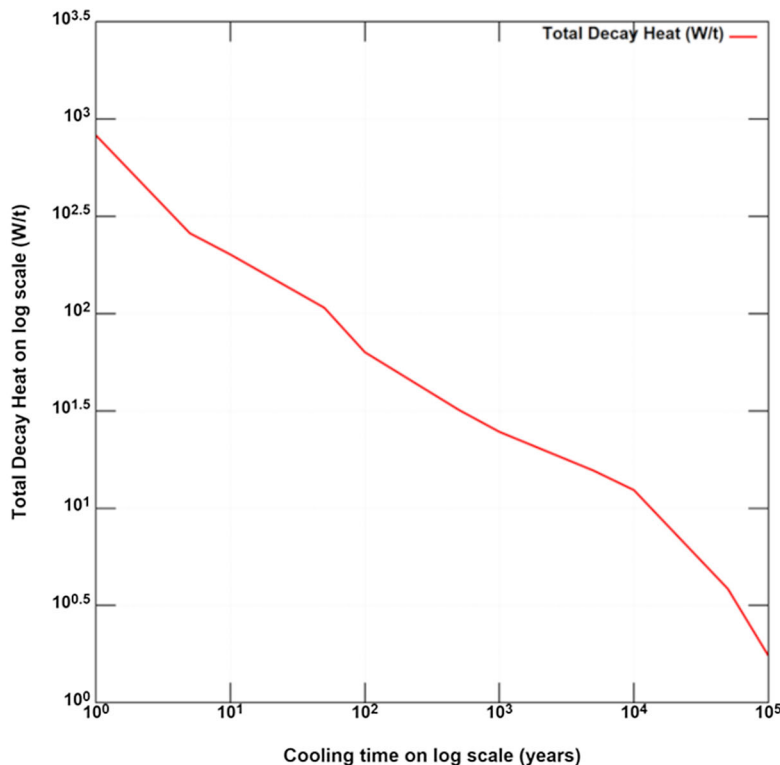
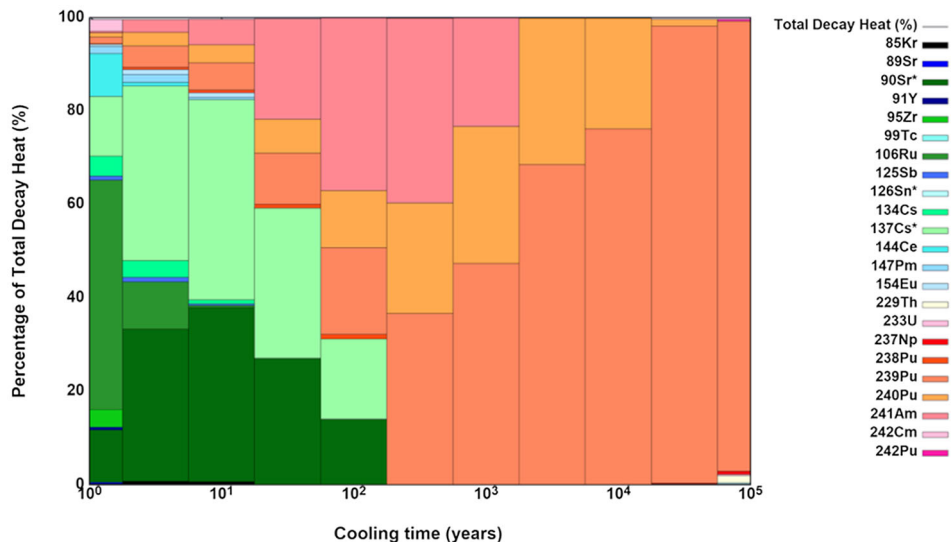


Fig. 2 Stacked Histogram depicting key radionuclides contributing over 99% of the total decay heat at each cooling time. An *parent radionuclides that incorporate energies from short-lived daughter products, e.g., 137Cs*, includes 137Cs and its short-lived daughter product 137mBa

Percentage of Total Decay Heat (%) vs Cooling Time (years) on linear vs log scale for 1t Magnox fuel at 3.62 MW_{th}



3.2 Nuclear data for identified nuclides of interest

3.2.1 Half-life

The half-lives for the nuclides of interest from the six evaluated libraries are given in Table 1. Note that the half-lives of shorter-lived decay products that are expected to be in equilibrium with a longer lived parent are not considered significant, and so are not listed. There are several isotopes where the half-life given in one library is inconsistent with the other evaluations. These are:

- 90Sr, half-life reported by JEF2.2 is 0.2–0.3 years longer than other libraries with a larger quoted uncertainty, and ENSDF is 0.1y longer than the other four libraries.

– ^{126}Sn , half-life reported by JEF2.2 is less than half that of the other libraries, with no quoted uncertainty.

3.2.2 Alpha decay energies

For mean alpha decay energies (Table 2) there are small variations between values in different libraries and their stated uncertainties for all the radionuclides of interest. The stated uncertainty for ^{237}Np in JEF2.2 and JEFF3.1.1 shows a very large discrepancy (at about 10%), while other radionuclides report much smaller uncertainties.

3.2.3 Mean beta decay and electron energies

The mean beta energies for the radionuclides of interest are given in Table 3, omitting those where the mean beta energy is less than 1 keV. There are several isotopes where the mean energy in one or more evaluated library is inconsistent with the other evaluations, which are:

- ^{85}Kr , where the JEFF3.1.1 value is about 10% lower than the other evaluations.
- ^{89}Sr , where the JEFF3.3 value is slightly lower and the ENSDF slightly higher.
- ^{90}Sr , where the JEFF3.1.1 value is about 10% lower than the other evaluations.
- ^{90}Y , where the DDEP value is slightly lower than the other evaluations.
- $^{95\text{m}}\text{Nb}$, where JEF2.2 does not report a mean energy, but a calculation of the difference between the reported total light particle energy and the discrete electron energies is more than twice the values in JEFF(3.1.1 and 3.3), ENDF/B-VIII.0 and ENSDF; and DDEP is less than half of these.

Table 1 Half-lives of nuclides of interest

Nuclide	Evaluated library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
^{85}Kr	$(10.720 \pm 0.010)\text{y}$	$(10.752 \pm 0.023)\text{y}$	$(10.752 \pm 0.023)\text{y}$	$(10.756 \pm 0.018)\text{y}$	$(10.739 \pm 0.014)\text{y}$	$(10.752 \pm 0.023)\text{y}$
^{89}Sr	$(50.50 \pm 0.10)\text{d}$	$(50.57 \pm 0.03)\text{d}$	$(50.57 \pm 0.03)\text{d}$	$(50.53 \pm 0.07)\text{d}$	$(50.563 \pm 0.025)\text{d}$	$(50.57 \pm 0.03)\text{d}$
^{90}Sr	$(29.121 \pm 0.24)\text{y}$	$(28.79 \pm 0.06)\text{y}$	$(28.80 \pm 0.07)\text{y}$	$(28.79 \pm 0.06)\text{y}$	$(28.90 \pm 0.03)\text{y}$	$(28.80 \pm 0.07)\text{y}$
^{91}Y	$(58.51 \pm 0.06)\text{d}$	$(58.51 \pm 0.06)\text{d}$	$(58.51 \pm 0.06)\text{d}$	$(58.51 \pm 0.06)\text{d}$	$(58.51 \pm 0.06)\text{d}$	–
^{95}Zr	$(63.98 \pm 0.06)\text{d}$	$(64.032 \pm 0.006)\text{d}$	$(64.032 \pm 0.006)\text{d}$	$(64.032 \pm 0.006)\text{d}$	$(64.032 \pm 0.006)\text{d}$	$(64.032 \pm 0.006)\text{d}$
^{99}Tc	$(213 \pm 5)\text{ky}$	$(214 \pm 8)\text{ky}$	$(211.5 \pm 1.1)\text{ky}$	$(211.1 \pm 1.2)\text{ky}$	$(211.0 \pm 1.2)\text{ky}$	$(211.4 \pm 1.1)\text{ky}$
^{106}Ru	$(368.2 \pm 1.2)\text{d}$	$(372.4 \pm 1.0)\text{d}$	$(371.3 \pm 2.1)\text{d}$	$(371.6 \pm 1.8)\text{d}$	$(371.8 \pm 1.8)\text{d}$	$(371.5 \pm 2.1)\text{d}$
^{125}Sb	$(2.726 \pm 0.03)\text{y}$	$(2.759 \pm 0)\text{y}$	$(2.759 \pm 0)\text{y}$	$(2.759 \pm 0)\text{y}$	$(2.757 \pm 0)\text{y}$	$(2.757 \pm 0)\text{y}$
^{126}Sn	$(100)\text{ky}$	$(230 \pm 14)\text{ky}$	$(230 \pm 14)\text{ky}$	$(230 \pm 14)\text{ky}$	$(230 \pm 14)\text{ky}$	–
$^{126\text{m}}\text{Sb}$	$(0.317 \pm 0.005)\text{h}$	$(0.318 \pm 0.003)\text{h}$	$(0.318 \pm 0.003)\text{h}$	$(0.319 \pm 0.001)\text{h}$	$(0.319 \pm 0.001)\text{h}$	–
^{126}Sb	$(12.4 \pm 0.1)\text{d}$	$(12.4 \pm 0.1)\text{d}$	$(12.41 \pm 0.05)\text{d}$	$(12.35 \pm 0.06)\text{d}$	$(12.35 \pm 0.06)\text{d}$	–
^{134}Cs	$(2.062 \pm 0.005)\text{y}$	$(2.065 \pm 0.001)\text{y}$	$(2.064 \pm 0.001)\text{y}$	$(2.065 \pm 0)\text{y}$	$(2.065 \pm 0)\text{y}$	$(2.064 \pm 0.001)\text{y}$
^{137}Cs	$(30.001 \pm 0.2)\text{y}$	$(30.041 \pm 0.03)\text{y}$	$(30.05 \pm 0.08)\text{y}$	$(30.081 \pm 0.09)\text{y}$	$(30.081 \pm 0.09)\text{y}$	$(30.051 \pm 0.08)\text{y}$
^{144}Ce	$(284.896 \pm 0.208)\text{d}$	$(285 \pm 0.2)\text{d}$	$(284.89 \pm 0.06)\text{d}$	$(284.91 \pm 0.05)\text{d}$	$(284.91 \pm 0.05)\text{d}$	$(284.89 \pm 0.06)\text{d}$
^{147}Pm	$(2.6231 \pm 0.0002)\text{y}$	$(2.623 \pm 0)\text{y}$	$(2.622 \pm 0.006)\text{y}$	$(2.623 \pm 0)\text{y}$	$(2.622 \pm 0)\text{y}$	$(2.622 \pm 0.004)\text{y}$
^{154}Eu	$(8.60 \pm 0.10)\text{y}$	$(8.593 \pm 0.004)\text{y}$	$(8.601 \pm 0.004)\text{y}$	$(8.601 \pm 0.01)\text{y}$	$(8.595 \pm 0.01)\text{y}$	$(8.595 \pm 0.004)\text{y}$
^{229}Th	$(7.34 \pm 0.16)\text{ky}$	$(7.34 \pm 0.16)\text{ky}$	$(7.34 \pm 0.16)\text{ky}$	$(7.34 \pm 0.16)\text{ky}$	$(7.34 \pm 0.16)\text{ky}$	–
^{233}U	$(159.3 \pm 0.2)\text{ky}$	$(159.3 \pm 0.2)\text{ky}$	$(159.3 \pm 0.2)\text{ky}$	$(159.2 \pm 0.2)\text{ky}$	$(159.1 \pm 0.2)\text{ky}$	–
^{237}Np	$(2140 \pm 10)\text{ky}$	$(2140 \pm 10)\text{ky}$	$(2144 \pm 7)\text{ky}$	$(2144 \pm 7)\text{ky}$	$(2143 \pm 7)\text{ky}$	$(2143 \pm 7)\text{ky}$
^{238}Pu	$(87.7 \pm 0.3)\text{y}$	$(87.7 \pm 0.3)\text{y}$	$(87.7 \pm 0.3)\text{y}$	$(87.70 \pm 0.10)\text{y}$	$(87.64 \pm 0.10)\text{y}$	$(87.68 \pm 0.03)\text{y}$
^{239}Pu	$(24.11 \pm 0.04)\text{ky}$	$(24.114 \pm 0.011)\text{ky}$	$(24.114 \pm 0.011)\text{ky}$	$(24.11 \pm 0.03)\text{ky}$	$(24.09 \pm 0.03)\text{ky}$	$(24.084 \pm 0)\text{ky}$
^{240}Pu	$(6.563 \pm 0.005)\text{ky}$	$(6.563 \pm 0.005)\text{ky}$	$(6.563 \pm 0.005)\text{ky}$	$(6.561 \pm 0.007)\text{ky}$	$(6.557 \pm 0.007)\text{ky}$	$(6.557 \pm 0.007)\text{ky}$
^{241}Pu	$(14.40 \pm 0.10)\text{y}$	$(14.33 \pm 0.04)\text{y}$	$(14.33 \pm 0.04)\text{y}$	$(14.29 \pm 0.01)\text{y}$	$(14.28 \pm 0.01)\text{y}$	$(14.32 \pm 0.04)\text{y}$
^{241}Am	$(432.7 \pm 0.5)\text{y}$	$(432.8 \pm 0.7)\text{y}$	$(432.8 \pm 0.7)\text{y}$	$(432.6 \pm 0.6)\text{y}$	$(432.3 \pm 0.6)\text{y}$	$(432.3 \pm 0.6)\text{y}$
^{242}Am	$(16.02 \pm 0.02)\text{h}$	$(16.04 \pm 0.03)\text{h}$	$(16.01 \pm 0.02)\text{h}$	$(16.02 \pm 0.02)\text{h}$	$(16.02 \pm 0.02)\text{h}$	$(16.01 \pm 0.02)\text{h}$
^{242}Cm	$(162.94 \pm 0.06)\text{d}$	$(162.93 \pm 0.07)\text{d}$	$(162.93 \pm 0.07)\text{d}$	$(162.94 \pm 0.06)\text{d}$	$(162.8 \pm 0.2)\text{d}$	$(162.86 \pm 0.08)\text{d}$
^{242}Pu	$(373.5 \pm 1.1)\text{ky}$	$(373.5 \pm 1.1)\text{ky}$	$(373.5 \pm 1.1)\text{ky}$	$(373.5 \pm 1.1)\text{ky}$	$(374.8 \pm 3.0)\text{ky}$	$(372.8 \pm 3.0)\text{ky}$
^{244}Cm	$(18.10 \pm 0.02)\text{y}$	$(18.00 \pm 0.10)\text{y}$	$(18.00 \pm 0.10)\text{y}$	$(18.11 \pm 0.03)\text{y}$	$(18.00 \pm 0.10)\text{y}$	$(18.11 \pm 0.03)\text{y}$

Data in bold italics identify discrepancies from the other libraries

Table 2 Mean alpha decay energies (MeV) for radionuclides of interest

Nuclide	Evaluated library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
213Bi	0.13 ± 0.01	0.13 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	–	0.12 ± 0.01
217At	7.07 ± 0.01	7.07 ± 0.01	7.07 ± 0.01	7.06 ± 0.01	7.06 ± 0.01	7.07 ± 0.01
221Fr	6.35 ± 0.05	6.35 ± 0.05	6.31 ± 0.02	6.36 ± 0.05	6.35 ± 0.05	6.31 ± 0.02
225Ac	5.76 ± 0.16	5.76 ± 0.16	5.79 ± 0.19	5.78 ± 0.16	5.78 ± 0.16	5.79 ± 0.19
229Th	4.86 ± 0.04	4.86 ± 0.04	4.86 ± 0.04	4.92 ± 0.03	4.92 ± 0.05	–
233U	4.82 ± 0.02	4.82 ± 0.02	4.82 ± 0.02	4.82 ± 0.02	4.81 ± 0.03	–
237Np	4.78 ± 0.42	4.78 ± 0.54	4.79 ± 0.02	4.79 ± 0.05	4.79 ± 0.05	4.79 ± 0.02
238Pu	5.49 ± 0.01	5.49 ± 0.01	5.49 ± 0.01	5.49 ± 0.01	5.49 ± 0.01	5.49 ± 0.01
239Pu	5.15 ± 0.04	5.15 ± 0.01	5.15 ± 0.01	5.15 ± 0.01	5.15 ± 0.01	5.15 ± 0.01
240Pu	5.16 ± 0.04	5.16 ± 0.04	5.16 ± 0.04	5.16 ± 0.01	5.16 ± 0.07	5.16 ± 0.01
241Am	5.48 ± 0.05	5.47 ± 0.02	5.47 ± 0.02	5.49 ± 0.03	5.49 ± 0.04	5.48 ± 0.01
242Cm	6.10 ± 0.04	6.10 ± 0.08	6.10 ± 0.08	6.10 ± 0.01	6.10 ± 0.01	6.10 ± 0.01
242Pu	4.89 ± 0.01	4.89 ± 0.01	4.89 ± 0.01	4.89 ± 0.01	4.89 ± 0.04	4.89 ± 0.01
244Cm	5.8	5.8	5.8	5.80 ± 0.01	5.80 ± 0.01	5.80 ± 0.03

Data in bold italics identify discrepancies from the other libraries

Table 3 Mean beta energies from different evaluated libraries (keV)

Nuclide	Evaluated library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
85Kr	250.49	228.11 ± 0.80	250.11 ± 0.70	250.60 ± 0.79	250.70 ± 0.09	250.51 ± 0.80
89Sr	582.3	584.6 ± 1.0	580.9 ± 0.9	585.3 ± 0.9	587.1 ± 1.1	584.6 ± 1.0
90Sr	195.6	174.0 ± 0.5	193.5 ± 0.5	195.8 ± 0.8	195.7 ± 0.5	196.0 ± 1.0
90Y	932.4	933.6 ± 1.2	933.6 ± 1.2	932.8 ± 0.7	932.3 ± 0.7	926.6 ± 0.8
91Y	609.3	605.9 ± 0.9	605.9 ± 0.9	603.0 ± 0.8	603.0 ± 0.9	–
95Zr	115.7	117.3 ± 0.7	117.4 ± 0.6	117.0 ± 0.6	117.0 ± 0.7	117.3 ± 0.7
95mNb	51.8 ± 15.9	21.8 ± 3.1	21.8 ± 3.1	22.1	22.1 ± 4.5	8.3 ± 0.3
95Nb	43.33	43.44 ± 0.15	43.49 ± 0.15	43.43 ± 0.15	43.43 ± 0.15	43.44 ± 0.15
99Tc	85.0	85.4 ± 0.6	95.3 ± 0.4	55.2 ± 0.3	84.6 ± 0.5	94.6 ± 1.7
106Ru	10.04	10.10 ± 0.10	10.04 ± 0.05	10.03 ± 0.08	10.03 ± 0.08	10.03 ± 0.06
106Rh	1412	1411 ± 12	1412 ± 6	1413 ± 12	1410 ± 18	1414 ± 6
125Sb	86.5	87.0 ± 2.0	86.5 ± 2.0	86.6 ± 2.0	86.7 ± 2.2	86.5 ± 2.0
126Sn	83.6	70.0 ± 10.0	70.0 ± 10.0	70.8 ± 9.5	70.0 ± 10.0	–
126mSb	619.0	613.5	613.5	638.0	639.6 ± 60.8	–
126Sb	352.6	334.4 ± 38.3	321.3 ± 15.3	354.9 ± 46.8	354.9 ± 46.8	–
134Cs	157.2	157.1 ± 0.9	157.1 ± 0.4	157.3 ± 0.7	157.2 ± 0.7	157.3 ± 0.5
137Cs	186.0	187.9 ± 0.9	179.9 ± 0.9	179.4 ± 0.7	187.1 ± 0.1	188.0 ± 1.3
144Ce	82.1	82.2 ± 1.0	78.6 ± 0.4	82.3 ± 0.6	82.1 ± 0.9	82.5 ± 0.4
144Pr	1204.4	1200.6	1206.0 ± 1.1	1208.0 ± 5.0	1208.5 ± 5.0	1208.5 ± 0.1
147Pm	61.88	61.96 ± 1.00	61.76 ± 0.01	61.78 ± 0.09	61.93 ± 0.01	61.80 ± 0.10
154Eu	221.2	221.2	220.5 ± 3.6	221.3 ± 0.1	220.0 ± 10.0	221.2 ± 3.7
209Pb	197.34	197.34	197.17 ± 0.42	197.40 ± 0.39	197.50 ± 0.40	197.35 ± 0.42
213Bi	426.6	426.6	426.6 ± 2.8	424.0 ± 2.6	435.0 ± 3.0	426.0 ± 2.8
225Ra	94.0	94.0	92.7 ± 2.9	92.4 ± 2.6	97.0 ± 5.0	92.2 ± 2.9
241Pu	5.24	5.23	5.10 ± 0.05	5.23 ± 0.05	5.23 ± 0.04	5.80 ± 0.10
242Am	158.0	160.0	160.0 ± 6.3	159.1 ± 13.6	157.8 ± 13.7	159.8 ± 6.3

Data in bold italics identify discrepancies from the other libraries

- ^{99}Tc , where the ENDF/B-VIII.0 value is significantly lower, and JEFF3.3 and DDEP values significantly higher than the mean of the other three evaluations.
- ^{126}mSb , where the ENDF/B-VIII.0 and ENSDF values are about 5% higher than the other evaluations.
- ^{137}Cs , where the JEFF3.3 and ENDF values are about 5% lower than the other evaluations.
- ^{144}Ce , where the JEFF3.3 value is about 5% lower than the other evaluations.

The total of auger and conversion electrons (CE) for each isotope of interest are given in Table 4, omitting those where the total energy is less than 0.1 keV. The most significant isotopes where there are variations between evaluations are:

- ^{95}mNb , where the value for JEF2.2 is very low, and the other evaluations give values of either 156keV or 163keV.
- ^{106}Rh where the energies for the ENSDF and DDEP evaluations are much lower than for the other evaluations.
- ^{125}Sb where the DDEP value is much larger than the other evaluations.
- ^{126}Sb , where the JEFF3.1.1 values is much lower than the other evaluations.
- ^{225}Ac , where the ENDF/B-VIII.0 value is larger but with large uncertainties.
- ^{229}Th , where the ENDF/B-VIII.0 value is larger and ENSDF is lower than the other evaluations.
- ^{229}Th , where the ENDF/B-VIII.0 value is larger and ENSDF is lower than the other evaluations.
- ^{237}Np , where the JEF2.2 value is larger and JEFF3.1.1 is lower than the other evaluations.

Table 4 Mean total discrete electron energies (CE+Auger) from different evaluated libraries (keV)

Nuclide	Evaluated library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
^{90}Y	–	0.20 ± 0.02	0.20 ± 0.02	0.20 ± 0.04	0.20 ± 0.01	0.27 ± 0.12
^{95}Zr	–	2.75 ± 0.2	1.00 ± 0.03	1.00 ± 0.01	2.65 ± 0.09	1.74 ± 0.05
^{95}mNb	115.74 ± 2.2	156.87 ± 3.74	162.76 ± 6.08	156.5	156.33 ± 1.38	163.29 ± 1.53
^{95}Nb	–	1.08 ± 0.04	1.08 ± 0.04	1.09 ± 0.01	1.09 ± 0.01	1.08 ± 0.03
^{106}Rh	0.82	0.76 ± 0.03	0.80 ± 0.02	0.86 ± 0.10	0.09 ± 0.01	0.009 ± 0.001
^{125}Sb	12.68 ± 0.47	14.18 ± 0.46	12.78 ± 0.42	13.51 ± 0.32	12.91 ± 0.09	37.80 ± 0.51
^{126}Sn	52.24 ± 1.98	52.09 ± 2.65	52.09 ± 2.65	50.77 ± 2.88	51.76 ± 2.54	–
^{126}mSb	9.00 ± 0.23	11.25 ± 0.54	11.25 ± 0.54	10.96 ± 0.66	10.58 ± 0.50	–
^{126}Sb	9.83	2.34 ± 0.09	11.93	10.45 ± 0.58	10.25 ± 0.18	–
^{134}Cs	6.78 ± 0.37	6.54 ± 0.14	6.79 ± 0.15	6.81 ± 0.05	6.59 ± 0.01	6.45 ± 0.05
^{137}Cs	60.76 ± 5.44	57.33 ± 1.69	57.3 ± 1.68	60.74 ± 0.67	60.77 ± 0.70	59.21 ± 0.94
^{144}Ce	9.54 ± 0.23	9.06 ± 0.26	8.84 ± 0.25	9.05 ± 0.13	9.44 ± 0.11	9.33 ± 0.20
^{144}mPr	44.95 ± 0.84	46.97	44.68 ± 1.35	44.86 ± 5.6	44.99 ± 0.05	45.19 ± 0.78
^{154}Eu	44.84 ± 3.33	53.28 ± 3.12	49.71 ± 1.09	51.41 ± 0.50	51.03 ± 0.52	48.08 ± 0.56
^{213}Bi	17.73 ± 1.56	17.73 ± 1.56	17.44 ± 0.64	17.61 ± 0.21	17.40 ± 0.21	17.45 ± 0.29
^{221}Fr	8.82 ± 0.54	8.82 ± 0.54	8.06 ± 0.22	8.25 ± 0.14	8.41 ± 0.05	7.92 ± 0.09
^{225}Ac	27.61 ± 0.72	27.61 ± 0.72	20.08 ± 0.50	38.49 ± 14.71	14.73 ± 1.37	21.22 ± 0.45
^{225}Ra	13.82 ± 0.93	13.82 ± 0.93	10.49 ± 0.56	12.03 ± 1.34	10.05 ± 0.31	11.82 ± 0.49
^{229}Th	115.9 ± 2.8	115.9 ± 2.8	115.9 ± 2.8	144.9 ± 17.5	100.5 ± 6.5	–
^{233}U	7.60 ± 0.43	7.60 ± 0.43	7.60 ± 0.43	5.04 ± 0.54	4.46 ± 0.55	–
^{237}Np	69.86 ± 2.97	38.31 ± 1.53	54.20 ± 1.71	45.94 ± 0.58	54.63 ± 0.85	53.16 ± 1.43
^{238}Pu	11.19 ± 0.75	11.19 ± 0.75	11.19 ± 0.75	9.43 ± 0.14	8.48 ± 0.13	9.34 ± 0.49
^{239}Pu	7.39 ± 0.36	7.93 ± 0.38	7.93 ± 0.38	5.77 ± 0.06	5.67 ± 0.06	5.51 ± 0.08
^{240}Pu	11.12 ± 0.73	11.12 ± 0.73	11.12 ± 0.73	9.34 ± 0.13	8.43 ± 0.14	9.41 ± 0.20
^{241}Am	39.27 ± 1.88	33.04 ± 1.66	33.04 ± 1.66	20.51 ± 0.43	27.07 ± 0.99	28.95 ± 1.06
^{242}Am	22.68	22.73	15.34 ± 0.59	18.79 ± 1.36	14.63 ± 0.19	16.05 ± 0.44
^{242}Cm	10.17 ± 0.66	10.17 ± 0.66	10.17 ± 0.66	8.66 ± 0.08	6.91 ± 0.07	7.81 ± 0.16
^{242}Pu	9.38 ± 0.64	9.38 ± 0.64	9.38 ± 0.64	7.96 ± 0.11	7.63 ± 0.11	7.94 ± 0.14
^{244}Cm	14.14	8.87	8.87	7.65 ± 0.57	9.12 ± 0.66	5.93 ± 0.13

Data in bold italics identify discrepancies from the other libraries

Table 5 Mean gamma energies from different evaluated libraries (keV)

Nuclide	Evaluated Library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
85Kr	2.21 ± 0.05	2.24 ± 0.05	2.24 ± 0.05	2.23 ± 0.05	2.23 ± 0	2.24 ± 0.05
91Y	3.61 ± 0.84	3.13 ± 0.48	3.13 ± 0.48	3.13 ± 0.48	3.14 ± 0.04	–
95Zr	737.0 ± 4.9	732.8 ± 2.3	732.1 ± 2.3	732.1 ± 2.3	732.7 ± 2.3	732.8 ± 2.3
95mNb	61.26 ± 1.41	63.55 ± 0.78	63.96 ± 0.74	63.59 ± 1.89	63.53 ± 1.89	63.94 ± 0.74
95Nb	765.83 ± 0.04	764.47 ± 0.06	764.47 ± 0.06	764.50 ± 0.06	764.47 ± 0.06	764.47 ± 0.06
106Rh	208.63 ± 4.93	204.27 ± 2.85	205.07 ± 1.54	206.05 ± 2.60	209.49 ± 1.58	205.07 ± 1.54
125Sb	420.55 ± 1.97	423.07 ± 2.04	421.03 ± 1.71	420.17 ± 2.03	420.17 ± 1.58	421.66 ± 1.71
126Sn	48.31 ± 1.49	48.35 ± 3.82	48.35 ± 3.82	48.33 ± 3.82	48.31 ± 1.50	–
126mSb	1547.8 ± 34.8	1573.8 ± 50.4	1573.8 ± 50.4	1547.9 ± 53.8	1549.7 ± 48.7	–
126Sb	2752.8	2777.0 ± 47.7	2751.5 ± 29.5	2755.0 ± 54.0	2752.2 ± 54.2	–
134Cs	1553.7 ± 9.7	1555.2 ± 0.5	1554.4 ± 0.9	1554.2 ± 0.9	1554.2 ± 0.9	1554.4 ± 0.9
137Cs	562.82 ± 2.50	562.58 ± 1.25	562.34 ± 1.25	563.30 ± 0.88	563.07 ± 1.32	562.34 ± 1.32
137mBa	594.95 ± 2.65	595.95 ± 1.32	595.95 ± 1.32	594.83 ± 0.93	594.83 ± 0.93	595.95 ± 1.32
144Ce	16.17 ± 0.16	15.93 ± 0.29	15.88 ± 0.17	16.17 ± 0.26	16.16 ± 0.26	15.88 ± 0.17
144mPr	0.05	1.64	0.05	1.83 ± 0.22	0.90 ± 0.09	1.49 ± 0.18
144Pr	28.90	29.37	30.26	28.86 ± 0.36	28.86 ± 0.34	30.26 ± 0.54
154Eu	1213.3 ± 12.0	1233.7 ± 2.6	1232.7 ± 4.8	1231.1 ± 5.1	1228.5 ± 6.6	1234.8 ± 4.8
213Bi	125.13 ± 1.85	125.13 ± 1.85	123.82 ± 1.33	123.31 ± 0.69	122.58 ± 0.69	123.35 ± 1.33
221Fr	26.67 ± 0.39	26.67 ± 0.39	26.25 ± 0.33	26.15 ± 0.59	26.25 ± 0.06	26.25 ± 0.33
225Ac	11.12 ± 0.53	11.12 ± 0.53	10.79 ± 0.15	10.13 ± 0.22	10.13 ± 0.15	10.79 ± 0.15
225Ra	12.00 ± 0.41	12.00 ± 0.41	12.03 ± 0.28	12.00 ± 0.41	12.00 ± 0.30	12.03 ± 0.28
229Th	34.41 ± 0.97	34.41 ± 0.97	34.41 ± 0.97	39.09 ± 0.76	39.15 ± 0.73	–
237Np	19.50 ± 1.50	19.48 ± 0.30	19.20 ± 0.23	19.92 ± 0.30	19.05 ± 0.30	19.55 ± 0.23
241Am	22.60 ± 0.24	22.41 ± 0.07	22.41 ± 0.07	22.12 ± 0.22	22.12 ± 0.24	22.15 ± 1.67

Data in bold italics identify discrepancies from the other libraries

3.2.4 Mean gamma and X-ray energies

The mean gamma ray energies for the isotopes of interest are given in Table 5. Note a threshold of 1 keV was set for radionuclides displayed in Table 5, to omit less significant gamma energy values. The most significant variations between evaluated libraries are:

- 154Eu, where the JEF2.2 value is lower with larger uncertainty.
- 229Th, where the values from JEF2.2, JEFF3.1.1 and JEFF3.3 are more than 10% lower than the ENDF/B-VIII.0 and ENSDF evaluations.

The mean X-ray energies for the isotopes of interest are given in Table 6. Note a threshold of 0.1 keV was set for radionuclides displayed in Table 6, to omit less significant X-ray energy values. This part of the analysis reveals a significant number of radionuclides with X-ray variation between the evaluated libraries, which are:

- 95mNb, where JEF2.2 is approximately 20% lower than the other evaluations.
- 125Sb, where DDEP is approximately 30% higher than the other evaluations.
- 126mSb, where JEF2.2 is approximately higher by a factor of 7 compared with other evaluations.
- 154Eu, where JEF2.2 is approximately 45% higher than the other evaluations.
- 221Fr, where ENDF/B-VIII.0 and ENSDF is slightly lower to the other evaluations.
- 225Ac, where ENSDF is slightly lower than the other evaluations.
- 229Th, where ENDF/B-VIII.0 is slightly higher than other evaluations, but with larger uncertainty.
- 238Pu, where ENSDF is approximately 70% lower than the other evaluations.
- 239Pu, where ENDF/B-VIII.0 is approximately half that of the other evaluations.
- 240Pu, where ENDF/B-VIII.0 and DDEP libraries are slightly higher than the other evaluations.
- 241Am, where ENDF/B-VIII.0 and DDEP libraries are slightly out of range including uncertainties from the other evaluations.
- 242Pu, where ENDF/B-VIII.0 and DDEP libraries are slightly out of range including uncertainties from the other evaluations.

Table 6 Mean X-ray energies from different evaluated libraries (keV)

Key FP's	Evaluated Library					
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF	DDEP
95mNb	5.49 ± 0.28	7.14 ± 0.24	7.39 ± 0.30	7.13 ± 0.45	7.12 ± 0.14	7.37 ± 0.20
125Sb	13.19 ± 0.73	13.96 ± 0.68	13.13 ± 0.56	13.21 ± 0.81	12.91 ± 0.23	19.18 ± 0.40
126Sn	8.46 ± 0.50	8.55 ± 0.48	8.55 ± 0.48	8.29 ± 0.62	8.16 ± 0.40	–
126mSb	2.96 ± 0.13	0.43 ± 0.02	0.43 ± 0.02	0.41 ± 0.03	0.41 ± 0.02	–
126Sb	0.53	0.11	0.56 ± 0.03	0.48 ± 0.03	0.47 ± 0.01	–
134Cs	0.28 ± 0.02	0.28 ± 0.01	0.28 ± 0.01	0.28 ± 0.02	0.27 ± 0	0.28 ± 0
137Cs	2.32 ± 0.14	2.30 ± 0.07	2.30 ± 0.07	2.30 ± 0.04	2.30 ± 0.04	2.30 ± 0.03
144Ce	3.28 ± 0.06	3.12 ± 0.09	3.07 ± 0.08	3.08 ± 0.19	3.21 ± 0.05	3.23 ± 0.04
144mPr	11.81 ± 0.24	12.19	11.8 ± 0.4	11.65 ± 0.22	11.52 ± 0.17	11.66 ± 0.17
154Eu	16.73 ± 0.99	11.34 ± 0.66	11.66 ± 0.31	11.66 ± 0.69	11.50 ± 0.20	11.66 ± 0.16
213Bi	3.29 ± 0.18	3.29 ± 0.18	3.26 ± 0.10	3.22 ± 0.18	3.13 ± 0.04	2.85 ± 0.28
221Fr	3.16 ± 0.17	3.16 ± 0.17	3.01 ± 0.10	2.42 ± 0.20	2.74 ± 0.10	3.02 ± 0.10
225Ac	6.03 ± 0.33	6.03 ± 0.33	5.66 ± 0.31	5.25 ± 0.55	3.78 ± 0.45	5.63 ± 0.18
225Ra	1.83 ± 0.18	1.83 ± 0.18	1.89 ± 0.21	1.98 ± 0.13	1.75 ± 0.06	2.03 ± 0.09
229Th	55.90 ± 2.83	55.90 ± 2.83	55.90 ± 2.83	64.74 ± 7.94	54.25 ± 1.60	–
233U	1.01 ± 0.10	1.01 ± 0.10	1.01 ± 0.10	0.89 ± 0.11	0.69 ± 0.14	–
237Np	14.02 ± 0.86	12.92 ± 0.77	12.73 ± 0.78	12.18 ± 0.64	11.26 ± 0.34	15.43 ± 0.52
238Pu	1.52 ± 0.15	1.52 ± 0.15	1.52 ± 0.15	1.83 ± 0.13	0.50 ± 0.07	1.72 ± 0.01
239Pu	0.65 ± 0.06	0.66 ± 0.06	0.66 ± 0.06	0.30 ± 0.03	0.60 ± 0.03	0.78 ± 0.01
240Pu	1.33 ± 0.13	1.33 ± 0.13	1.33 ± 0.13	1.73 ± 0.13	1.31 ± 0.05	1.67 ± 0.02
241Am	5.60 ± 0.54	5.10 ± 0.49	5.10 ± 0.49	4.21 ± 0.28	5.15 ± 0.42	6.42 ± 0.03
242Am	17.29	16.66	17.83 ± 0.58	18.35	16.75 ± 0.55	16.84 ± 0.42
242Cm	1.35 ± 0.13	1.35 ± 0.13	1.35 ± 0.13	1.89 ± 0.13	1.42 ± 0.06	1.75 ± 0.04
242Pu	1.23 ± 0.12	1.23 ± 0.12	1.23 ± 0.12	1.49 ± 0.11	1.17 ± 0.05	1.45 ± 0.04
244Cm	1.28	1.18	1.18	1.73 ± 0.20	1.29 ± 0.19	1.52 ± 0.04

Values which show discrepancies are in bold italics

3.2.5 Fission yields

The cumulative fission yield is also an important variable to assess when comparing confidence levels in decay heat measurements for waste management and heat production. The cumulative yields following thermal fission of ²³⁵U are shown in Table 7 where it can be seen that the fission yields are consistent across all libraries. Cumulative fission yields for ²³⁹Pu are similarly consistent across all evaluations and are shown in Table 10 within “Appendix”.

Referring to Table 7, it is noted that the uncertainties reported for ⁹⁰Y and ⁹¹Y in the ENDF/B-VIII.0 library by JANIS are anomalously high, and as these should be almost identical to the cumulative yields of the parent isotopes where the uncertainties are approximately 1% in both cases, which clearly reflects an error somewhere.

Independent thermal fission yield data from ²³⁵U and ²³⁹Pu were also taken from the chosen libraries. Note that the ENSDF library gives independent fission yields, but not cumulative yields, and although these could be calculated by summing the independent yields for nuclides in the decay chains this has not been done as it would be expected that the results would be very similar to the values from the other evaluations. The DDEP library only reports decay data and does not include fission yields. Independent thermal fission yield data for both ²³⁵U and ²³⁹Pu are tabulated within “Appendix” in Tables 11 and 12, respectively, where the analysis of these are beyond the scope of the paper.

3.2.6 Thermal capture cross-sectional assessment

Neutron capture processes inside a reactor are also important to consider when assessing decay heat confidence levels. This process is a primary and secondary mode of production for actinides and fission products, respectively, as well as the activation of non-fuel elements within a reactor (which are not considered here). Table 8 lists the thermal neutron capture cross sections for the isotopes of interest (which relate to burn-up reducing their concentrations within a reactor) and also for the N-1 isotopes where the cross sections are > 1 b and are likely to be present in significant quantities (which relate to production of the isotopes of interest within a reactor). There are several examples where the cross sections tabulated vary by an order of magnitude or more between different

Table 7 Cumulative fission yield due to ^{235}U (%). No data from ENSDF database so omitted from table

Nuclide	Evaluated library			
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0
85Kr	$(2.9 \pm 0.1) \times 10^{-1}$	$(2.9 \pm 0.2) \times 10^{-1}$	$(3.0 \pm 0.2) \times 10^{-1}$	$(2.8 \pm 0) \times 10^{-1}$
89Sr	$(477 \pm 35.3) \times 10^{-2}$	$(470 \pm 5.7) \times 10^{-2}$	$(470 \pm 6.6) \times 10^{-2}$	$(470 \pm 4.7) \times 10^{-2}$
90Sr	$(58.5 \pm 1.9) \times 10^{-1}$	$(57.3 \pm 1.3) \times 10^{-1}$	$(56.8 \pm 1.3) \times 10^{-1}$	$(57.8 \pm 0.6) \times 10^{-1}$
90Y	$(58.5 \pm 1.9) \times 10^{-1}$	$(57.3 \pm 1.3) \times 10^{-1}$	$(56.8 \pm 1.3) \times 10^{-1}$	$(57.8 \pm 37.0) \times 10^{-1}$
91Y	$(58.8 \pm 0.8) \times 10^{-1}$	$(58.5 \pm 0.5) \times 10^{-1}$	$(58.5 \pm 0.5) \times 10^{-1}$	$(58.3 \pm 37.3) \times 10^{-1}$
95Zr	$(656 \pm 24.4) \times 10^{-2}$	$(650 \pm 7.2) \times 10^{-2}$	$(650 \pm 6.5) \times 10^{-2}$	$(650 \pm 9.1) \times 10^{-2}$
95mNb	$(72.8 \pm 2.7) \times 10^{-3}$	$(70.2 \pm 6.7) \times 10^{-3}$	$(70.3 \pm 7.0) \times 10^{-3}$	$(65.1 \pm 0.9) \times 10^{-3}$
95Nb	$(656 \pm 0.2) \times 10^{-2}$	$(650 \pm 7.2) \times 10^{-2}$	$(650 \pm 6.5) \times 10^{-2}$	$(650 \pm 9.1) \times 10^{-2}$
99Tc	$(618 \pm 0.4) \times 10^{-2}$	$(613 \pm 9.2) \times 10^{-2}$	$(614 \pm 8.0) \times 10^{-2}$	$(611 \pm 6.1) \times 10^{-2}$
106Ru	$(40.7 \pm 1.5) \times 10^{-2}$	$(41.0 \pm 1.1) \times 10^{-2}$	$(41.0 \pm 0.9) \times 10^{-2}$	$(40.2 \pm 0.6) \times 10^{-2}$
106Rh	$(40.7 \pm 1.5) \times 10^{-2}$	$(41.0 \pm 1.1) \times 10^{-2}$	$(41.0 \pm 0.9) \times 10^{-2}$	$(40.2 \pm 0.6) \times 10^{-2}$
125Sb	$(27.8 \pm 1.7) \times 10^{-3}$	$(26.0 \pm 1.4) \times 10^{-3}$	$(30.3 \pm 1.3) \times 10^{-3}$	$(34.0 \pm 1.0) \times 10^{-4}$
126Sn	$(59.7 \pm 5.5) \times 10^{-3}$	$(52.9 \pm 5.0) \times 10^{-3}$	$(57.7 \pm 1.9) \times 10^{-3}$	$(56.1 \pm 4.5) \times 10^{-3}$
126mSb	$(59.7 \pm 5.5) \times 10^{-3}$	$(4.0 \pm 1.0) \times 10^{-3}$	$(51.2 \pm 12.2) \times 10^{-3}$	$(57.9 \pm 4.6) \times 10^{-3}$
126Sb	$(89.3 \pm 8.4) \times 10^{-4}$	$(29.1 \pm 8.5) \times 10^{-4}$	$(3.7 \pm 1.0) \times 10^{-4}$	$(87.5 \pm 14.0) \times 10^{-4}$
134Cs	$(20.3 \pm 7.6) \times 10^{-6}$	$(12.1 \pm 3.3) \times 10^{-6}$	$(17.4 \pm 4.8) \times 10^{-7}$	$(7.7 \pm 4.9) \times 10^{-6}$
137Cs	$(624 \pm 53.9) \times 10^{-2}$	$(622 \pm 6.9) \times 10^{-2}$	$(609 \pm 6.3) \times 10^{-2}$	$(619 \pm 3.1) \times 10^{-2}$
137mBa	$(591 \pm 16.3) \times 10^{-2}$	$(587 \pm 8.4) \times 10^{-2}$	$(575 \pm 7.9) \times 10^{-2}$	$(585 \pm 2.9) \times 10^{-2}$
144Ce	$(546 \pm 15.8) \times 10^{-2}$	$(547 \pm 5.5) \times 10^{-2}$	$(548 \pm 4.9) \times 10^{-2}$	$(550 \pm 3.9) \times 10^{-2}$
144mPr	$(82.0 \pm 2.4) \times 10^{-3}$	$(75.6 \pm 6.0) \times 10^{-3}$	$(75.6 \pm 5.7) \times 10^{-3}$	$(27.5 \pm 0.2) \times 10^{-3}$
144Pr	$(546 \pm 15.8) \times 10^{-2}$	$(547 \pm 5.5) \times 10^{-2}$	$(548 \pm 4.9) \times 10^{-2}$	$(550 \pm 2.8) \times 10^{-2}$
147Pm	$(227 \pm 18.9) \times 10^{-2}$	$(223 \pm 4.0) \times 10^{-2}$	$(223 \pm 4.0) \times 10^{-2}$	$(225 \pm 2.3) \times 10^{-2}$
154Eu	$(3.2 \pm 1.2) \times 10^{-7}$	$(2.0 \pm 0.6) \times 10^{-7}$	$(5.8 \pm 1.7) \times 10^{-9}$	$(1.9 \pm 1.2) \times 10^{-7}$

evaluations. The different evaluations give values for these cross sections without a stated uncertainty, and no information on the primary data used to produce these values. Therefore, as the information needed to assess the primary data is not readily available within the evaluated libraries, further examination of these differences have not been attempted and is beyond the scope of this paper. However, there is clearly a need to resolve the significant differences between these evaluations and determine cross sections that can be used with confidence.

3.3 Radionuclides where discrepancies between libraries are observed

The observations quoted within this paper are summarized in Table 9, listing those radionuclides where there are observed discrepancies between evaluations.

From the discrepancies in decay data given in Table 9, those isotopes that are most significant in nuclear waste management and heat production have been investigated in more detail below. Of the remaining isotopes the discrepancies are either very small or have relatively simple explanations. For ^{85}Kr , the beta energy discrepancy follows the use of an allowed transition of the dominant (> 99%) decay to the ^{85}Rb ground state in JEFF3.1.1 whereas the other evaluations use a physically more reasonable first forbidden transition. For ^{106}Rh , where the differences account for < 1 keV in electron energy, the DDEP evaluators do not include any conversion electrons and the ENSDF evaluators list 9, of which 5 are given with zero intensity, whereas the other evaluations include a much larger number of conversion electrons with greater intensities. The JEF2.2 evaluation conducted in 1982 for ^{154}Eu used gamma energy and intensity data from [14]—the other evaluations include data from several more recent measurements and although the differences in gamma ray energies and intensities are small, the cumulative differences across over 100 emissions accounts for the approximate 20 keV difference between the JEF2.2 and later evaluations. For ^{229}Th , the JEF2.2, JEFF3.1.1 and JEFF3.3 share the same 1980 evaluation, with ENDF/B-VIII.0 and ENSDF incorporating more recent experimental data. ^{237}Np alpha decay data for JEF2.2 and JEFF3.1.1 have large uncertainties that are significantly reduced with more precise data in later evaluations.

Table 8 Thermal neutron capture cross sections (b) for isotopes of interest and relevant N-1 isotopes (*italic*). Values which show discrepancies are in bold

Nuclide	Evaluated library				
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF
85Kr	1.66	1.66	1.65	1.66	1.66
89Sr	0.420	0.420	0.418	0.420	0.420
90Sr	0.9003	0.9003	0.0354	0.0150	0.0150
89Y	1.286	1.286	1.279	1.279	1.278
90Y	3.50	3.50	6.46	3.30	3.30
91Y	1.40	1.40	1.40	1.40	1.40
95Zr	0.225	0.225	6.493	1.200	1.200
94Nb	13.61	15.77	15.77	15.77	15.76
95Nb	1.77	7.00	7.00	7.00	7.00
99Tc	19.1	22.8	22.8	20.0	22.8
106Ru	0.146	0.146	0.145	0.146	0.146
124Sb	6.502	6.502	17.34	17.41	17.40
125Sb	1.00	1.00	12.2	5.00	5.00
126Sn	0.300	0.300	1.792	0.090	0.090
126Sb	5.80	5.80	17.44	13.00	13.00
133Cs	29.1	29.0	29.1	29.1	29.0
134Cs	139.7	139.7	140.4	139.7	139.7
136Cs	1.30	1.30	11.94	13.00	13.00
137Cs	0.1415	0.1415	0.2685	0.2500	0.2501
143Ce	6.00	6.00	4.49	6.00	6.00
144Ce	1.13	1.13	1.00	1.00	1.00
147Pm	180.6	168.4	168.4	167.7	168.0
153Eu	299.7	312.6	312.6	358.0	312.5
154Eu	1501	1356	1353	1470	1352
228Th	–	119.9	122.9	122.9	119.9
229Th	–	63.38	70.56	70.56	63.38
233U	45.92	45.27	45.22	42.32	45.26
237Np	181.0	181.0	175.4	175.4	161.7
238Pu	546.1	540.1	412.8	412.8	560.8
239Pu	270.4	272.8	271.4	270.1	270.7
240Pu	288.7	285.8	285.8	287.5	287.5
241Pu	362.9	363.0	363.1	363.0	363.0
241Am	615.1	647.1	747.8	684.2	618.8
242Am	5500	219.0	218.8	219.0	219.0
242Cm	16.5	15.9	19.1	19.1	16.9
242Pu	18.5	18.8	18.8	21.3	19.2
244Cm	14.4	10.4	15.2	15.2	15.1

Data in bold italics identify discrepancies from the other libraries

3.3.1 90Sr

The data for 90Sr show discrepancies in both half-life and mean beta energies. For the half-life evaluations, Woods and Lucas [15] produced new data following the decay of a 500 MBq 90Sr over six years using IG25 ionization counters producing a half life of 10495 ± 4 d, and an evaluation producing a weighted mean with six previously published results giving a half-life of 10516 ± 21 d, this is noted by the DDEP [16] and ENDF/B-VIII.0 evaluators [17] who reject some previously published values on the same grounds as Woods and Lucas (1996). The DDEP evaluation also includes a value by Schrader (2004) [18] for 17 y of measurements on a 90Sr source giving a half-life of 10557 ± 11 d (replacing previous published measurements of the half-life from the same source) which was not available to Browne [17]. The DDEP and ENDF/B-VIII.0 evaluations produce very similar values of the half-life, heavily weighted by the Woods and Lucas (1996) value—JEFF3.1.1 and JEFF3.3 values also postdate and are likely to be heavily weighted to this 1996 value. The JEF2.2 evaluation predates this and incorporates earlier data with slightly longer half-life.

Table 9 Summary of observed discrepancies between evaluation

Radionuclide	Observed discrepancies
85Kr	Beta energy: JEFF3.1.1 about 10% lower
89Sr	Beta energy: JEFF3.1.1 slightly lower, ENSDF slightly higher
90Sr	Half-life: JEFF2.2 longer, ENDF/B-VIII.0 shorter Beta energy: JEFF3.1.1 about 10% lower 90Y beta energy slightly lower for DDEP
95mNb	Beta energy: JEF2.2 very high (with corresponding low energy for other electrons) and DDEP very low Electron energy: JEF2.2 very low, while other evaluations give values that differ by almost 5%
99Tc	Beta energy: ENDF/B-VIII.0 significantly lower, JEFF3.3 and DDEP significantly higher
106Rh	Electron energy: lower values for ENSDF and DDEP
126Sn	Half-life: JEF2.2 far shorter with no uncertainty
126mSb	Beta energy: ENDF/B-VIII.0 and ENSDF about 5% higher
126Sb	Electron energy: JEFF3.1.1 value much lower than other evaluations
137Cs	Beta energy: JEFF3.3 and ENDF/B-VIII.0 about 5% lower
144Ce	Beta energy: JEFF3.3 about 5% lower
154Eu	Gamma energy: JEF2.2 lower with larger uncertainties
225Ac	Electron energy: ENDF/B-VIII.0 higher value with large uncertainties
229Th	Half-life: ENSDF shorter with lower uncertainty Gamma energy: JEF2.2, JEFF(3.1.1 and 3.3) more than 10% lower than ENDF/B-VIII.0 and ENSDF Electron energy: ENDF/B-VIII.0 higher, ENSDF lower than the other evaluations
237Np	Alpha energy: Very large uncertainties on JEF2.2 and JEFF3.1.1 Electron energy: JEF2.2 higher and JEFF3.1.1 lower than the other evaluations

The ENSDF value given here [19] uses a weighted mean from just three long-term measurements of 10527 ± 51 d measured over 11 y [20], 10561 ± 14 d measured over 33 y [21] and the 10557 ± 11 d of Schrader (2004) [18] giving a weighted mean of 10558 ± 11 d. These are all longer than the Woods and Lucas (1996) value, and hence, a longer half-life is determined compared to other evaluations which have included the 1996 value. The Woods and Lucas (1996) half-life is inconsistent with the Martin et al. (1994) and Schrader (2004) values, the differences between them being 66 ± 15 d and 62 ± 12 d, respectively [18,21]. This inconsistency should be examined in more detail before selecting an evaluation that either incorporates the Woods and Lucas (1996) value or rejects it.

In addition to the application to time trajectory of heat generation from nuclear waste, the value of the half-life of 90Sr is also critical to many applications where this isotope is used as a calibration source (for example, in applying known doses for luminescence dating).

For the beta decay, all the evaluations use the same endpoint energy (546.0 ± 1.4 keV), however the JEFF3.1.1 evaluators calculate the mean energy using a shape 0 (allowed) transition. With the transition from the $0+$ ground state of 90Sr to the $2-$ ground state of 90Y, this cannot be an allowed transition, and the use of first forbidden shapes by the other evaluations is appropriate. Thus, it is concluded that the low value of the mean beta energy in the JEFF3.1.1 evaluation is incorrect, and any of the values in the other libraries should be used.

3.3.2 95mNb

The mean beta energy reported in the DDEP library is a lot lower than that reported in the other evaluations (8.3 keV vs 22 keV). For JEF2.2, the library lists the 5.6% beta-decay branch but it does not include any beta emissions in the library, and a mean energy has been calculated here from the difference between the mean energy for discrete electrons and the reported mean energy for all light particles. The mean energy for discrete electrons in JEF2.2 is reported lower than those within the other libraries, resulting in a higher mean beta energy. The discrepancy in the JEF2.2 value reflects incomplete data included in the evaluation and is not considered further here except to note that later and more complete evaluations are preferred. The incomplete data in JEF2.2 also contribute to the low total energy of other electron emissions. The low DDEP mean beta energy is almost entirely explained by the absence of the beta transition to the 95Mo ground state included in the other evaluations (for ENSDF this has an endpoint of 1160 keV, with a mean energy of 437.4 ± 0.2 keV and a $3.2 \pm 1.0\%$ intensity), with minor variations in mean energy and intensity of the other transitions. This is a first unique forbidden ($\frac{1^-}{2} \rightarrow \frac{5^+}{2}$) transition, and there is no obvious reason why it would not occur

with an intensity similar to that ascribed to it in ENSDF and other evaluations. The notes on the DDEP evaluation [22,23] do not explain why this transition has been omitted, and this appears to be an error in the DDEP evaluation. The variations in the total energy of discrete electrons reflects variations in the intensity of the dominant 216keV conversion electron with DDEP and JEFF3.3 evaluators giving this an intensity of $58.1 \pm 0.6\%$ and $58.0 \pm 2.7\%$, respectively, with ENSDF, ENDF/B-VIII.0 and JEFF3.1.1 evaluators giving this a lower intensity of $55.9 \pm 0.6\%$, $55.9 \pm 1.0\%$ and $56.0 \pm 1.7\%$, respectively.

3.3.3 ^{99}Tc

All evaluations agree that the beta emissions from ^{99}Tc are dominated by the ground state to ground state transition with a maximum energy of 293.5–293.8 keV for all evaluations, except ENSDF which gives this as 297.5 ± 1.0 keV [24] and an intensity of 100% or very slightly lower. The major difference between the libraries is the choice of decay shape. The JEF2.2 and ENDF/B-VIII.0 evaluations use an allowed, non-unique transition shape but yield very different mean energies. The JEFF3.1.1 and 3.3 evaluations use a first forbidden unique shape and also yield different mean energies, and the ENSDF and DDEP evaluations use a second forbidden shape. The ENSDF evaluation uses an experimentally derived shape by Reich and Schüpfertling [25], whereas the DDEP evaluator [26] uses a weighted evaluation of form factors from Feldman and Wu [27]. These form factors were recalculated by Lipnik and Sunier (1966), Snyder and Beard (1966) who were then recalculated by Behrens and Szybisz (1976), and Reich and Schüpfertling (1974) [25,28–30].

3.3.4 ^{126}Sn

The earlier evaluations of the ^{126}Sn half-life use an estimation from [31] based on the thermal yield of ^{235}U in the order of 10^5 y. This estimation has been supplanted by radiochemical analyses and specific activity measurements of 2.07×10^5 y [32] and 2.5×10^5 y [33] in the later evaluations.

3.3.5 ^{126}Sb and ^{126m}Sb

The JEF2.2, JEFF3.1.1 and JEFF3.3 evaluations of the mean beta energy give values approximately 20 keV less than the ENDF/B-VIII.0 and ENSDF evaluations. This reflects differences in the intensity of the dominant beta emission in the decay used by different evaluators. This is a non-unique allowed transition with an endpoint of 1915 ± 30 keV, with the intensity given as $80.8 \pm 5.2\%$ (JEF2.2), $79.5 \pm 4.0\%$ (JEFF3.1.1 and JEF3.3), $82.8 \pm 8.0\%$ (ENDF/B-VIII.0) and $83 \pm 8\%$ (ENSDF) [10]. The large uncertainties on these intensities results in the large uncertainty given for the mean beta energy.

The JEFF3.1.1 evaluation for ^{126}Sb lists a small number of discrete electron emissions, whereas the other evaluations list a much larger number of emissions. The JEFF3.1.1 evaluation omits the more intense emissions from the other evaluations, in particular conversion electrons with energies at 383 keV (1% intensity) and 635 keV (0.3% intensity) which together account for the majority of the discrepancy. Given that the JEFF3.1.1 evaluation appears to use an incomplete list of conversion electron emissions it is considered unreliable, the JEF3.3, ENDF/B-VIII.0 and ENSDF evaluations produce consistent values for the total discrete electron energy.

3.3.6 ^{144}Ce

For ^{144}Ce , it is unclear where the beta energy discrepancy for the JEF3.3 evaluation arises as all the evaluations agree on the end-point energies and intensities of the three beta transitions. Though it is noted that the transitions reported through JANIS (for the JEF/JEFF and ENDF/B-VIII.0 evaluations) are allowed non-unique whereas DDEP lists them as first-forbidden non-unique. With the decays involving a parity change and $\Delta I = 0$ or 1, these should be first-forbidden decays. Differences in the assumed shape will result in different mean energies, but this does not explain the difference between the JEF3.3 and other evaluations if the same shapes are used. Given that the DDEP evaluators explicitly use a physically realistic first-forbidden decay it is reasonable to take this as the best value for the mean energy, as this is consistent with all other values apart from JEFF3.3 which looks erroneous.

3.3.7 ^{137}Cs

The mean beta energy reported by the JEFF3.3 and ENDF/B-VIII.0 evaluations is approximately 5% lower than that reported by the other libraries. The differences reflect significant variations in the treatment of the transition to the ^{137}Ba ground state. This is a ($\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$) second forbidden transition; however, the JEF2.2, JEFF3.1.1 and ENDF/B-VIII.0 libraries describe this as an allowed non-unique transition, and JEFF3.3 as a first forbidden transition. The ENSDF and DDEP evaluators use the LOGFT program to determine a mean energy of 416.26 ± 0.08 keV, whereas ENDF uses SPEBETA to give a mean energy of 271.0 ± 0.1 keV. The other evaluations are not explicit in how this mean energy was derived, but the JEF2.2 and JEFF3.1.1 values are

consistent with ENSDF/DDEP, while the JEFF3.3 value is consistent with ENDF/B-VIII.0. Given the evidence that this is a second forbidden transition, the evaluations that use this shape function (or, produce mean energies consistent with this) are preferred, and the conclusion is that the ^{137}Cs mean beta energies reported by JEFF3.3. and ENDF/B-VIII.0 are in error.

3.3.8 ^{225}Ac

The discrete electron energies calculated from the different evaluations differ markedly. JEF2.2 and JEFF3.1.1 use the same data and give a total energy of 27.6 ± 0.7 keV, JEFF 3.3 and DDEP give slightly lower energies of 20.1 ± 0.5 keV and 21.2 ± 0.5 keV, respectively, while the ENSDF value is much lower at 14.7 ± 1.4 keV and ENDF/B-VIII.0 is much higher with large uncertainties at 38.4 ± 14.7 keV. The ENSDF evaluation also reports a lower X-ray energy. It seems unlikely that the large and imprecise ENDF/B-VIII.0 is the best value for this energy; however, it would take further study to determine the best value.

4 Conclusions

An assessment was conducted on nuclear data to identify possible inconsistencies and discrepancies on isotopes that could influence decay heat calculations from RWM procedures. The assessment used a simple reactor inventory and decay model, combined with consideration of prior literature, to identify the nuclides that contribute to the majority of the decay heat (cumulatively > 99 %) at different stages of storage and disposal between 1 and 100 k years. This produced a list of 43 isotopes of interest, including short-lived decay products. The approach of [5,6] was then followed to compare the nuclear data for each of these isotopes as reported in six different semi-independent evaluations, where significant discrepancies were noted to explore further.

The main potential issues identified were:

- ^{90}Sr , where the half-life values differ significantly depending on whether or not the evaluators include one of the experimental values which is significantly shorter than other measurements recorded over longer periods of time. The accuracy of these different long term measurements should be assessed to identify why there are discrepancies, and whether one or more of them include systematic errors. Further independent data on the half-life would also be of benefit. Since ^{90}Sr is an isotope commonly used for various applications requiring a calibrated activity, an accurate value for the half-life is essential for these applications.
- ^{95}mNb , where the beta decay energy reported by the DDEP evaluation appears to be in error, omitting beta decay to the ^{95}Mo ground state.
- ^{99}Tc , where the mean beta energy calculated by different evaluations varies with the assumed shape of the beta spectrum. The DDEP and ENSDF evaluations both use measured spectral shapes, but still differ by almost 10% in the mean energy reported. The shape of this decay spectrum needs further investigation, either through more thorough examination of the existing data or with additional experimental measurement.
- ^{126}Sb and $^{126\text{m}}\text{Sb}$, where the mean beta energy is approximately 20 keV less in JEF2.2/JEFF3.1.1/JEFF3.3 versus other evaluations, and a lack of discrete electron emissions was reported for ^{126}Sb within the JEFF3.1.1 library.
- ^{144}Ce , where the mean beta energy is approximately 5% lower in JEFF3.3 and ENDF/B-VIII.0 versus the other evaluations.
- ^{137}Cs , where the mean beta energy reported in the JEF3.3 and ENDF/B-VIII.0 evaluations appears to be incorrect, using different spectral shapes.
- ^{225}Ac , where discrete electron energies differ between approximately 13 keV across the libraries with ENDF/B-VIII.0 reporting the highest uncertainty at 38.4 ± 14.7 keV.

Other discrepancies were noted to be of lesser significance, including half-lives for ^{126}Sn (where the JEF2.2 value is just an order of magnitude estimate); mean beta energies for ^{85}Kr and ^{89}Sr ; energies for discrete electrons for ^{106}Rh , ^{126}Sn , ^{229}Th and ^{237}Np ; and the gamma energies for ^{229}Th .

Overall, FP's dominated the discrepancy analysis, which are defined as high decay heat contributors across the interim storage period (1 - 100 years). Actinides, however, whose decay heat dominance is noticed at the long-term disposal timescale (0.1–100 ky), showed only potential discrepancies in ^{237}Np alpha and ^{225}Ac electron energies. Overall, consistency in mean alpha energies is seen across the evaluated libraries which could be due to better measurements or easier modeling capabilities. For FP's, the modeling capabilities are hindered by different shape factors in beta energies (seen for ^{99}Tc) and limitations in detector measurements for both beta and gamma energies. These consistencies in alpha energies could ultimately ensure a higher accuracy in decay heat measurements, especially when radioactive waste awaits disposal into a future repository, versus during the interim storage period.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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A Appendices

A.1 Cumulative fission yield data due to ^{239}Pu

Table 10 depicts the cumulative fission yield data from the thermal fission of ^{239}Pu . The data here show a similar relationship to ^{235}U reported within the main body of the text.

A.2 Independent thermal fission yield data due to ^{235}U and ^{239}Pu

Within the different evaluations there are often significant variations in the independent thermal fission yields reported; Tables 11 and 12 display these values for ^{235}U and ^{239}Pu respectively. In some cases, an order of magnitude difference can be seen.

Table 10 Cumulative fission yield due to ^{239}Pu (%)

Nuclide	Evaluated library			
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0
85Kr	$(13.0 \pm 0.4) \times 10^{-2}$	$(13.6 \pm 1.4) \times 10^{-2}$	$(13.5 \pm 1.5) \times 10^{-2}$	1.2×10^{-1}
89Sr	$(168 \pm 8.7) \times 10^{-2}$	$(169 \pm 3.2) \times 10^{-2}$	$(171 \pm 2.6) \times 10^{-2}$	$(172 \pm 4.8) \times 10^{-2}$
90Sr	$(197 \pm 4.5) \times 10^{-2}$	$(201 \pm 5.4) \times 10^{-2}$	$(208 \pm 5.8) \times 10^{-2}$	$(210 \pm 4.2) \times 10^{-2}$
90Y	$(197 \pm 4.5) \times 10^{-2}$	$(201 \pm 5.4) \times 10^{-2}$	$(208 \pm 5.8) \times 10^{-2}$	$(210 \pm 135) \times 10^{-2}$
91Y	$(244 \pm 8.7) \times 10^{-2}$	$(244 \pm 2.9) \times 10^{-2}$	$(243 \pm 3.2) \times 10^{-2}$	$(249 \pm 159) \times 10^{-2}$
95Zr	$(42.9 \pm 1.2) \times 10^{-1}$	$(495 \pm 9.9) \times 10^{-2}$	$(488 \pm 5.4) \times 10^{-2}$	$(482 \pm 6.7) \times 10^{-2}$
95mNb	$(54.7 \pm 1.3) \times 10^{-3}$	$(53.5 \pm 6.6) \times 10^{-3}$	$(52.8 \pm 6.1) \times 10^{-3}$	$(48.3 \pm 0.1) \times 10^{-3}$
95Nb	$(492 \pm 11.6) \times 10^{-2}$	$(495 \pm 9.9) \times 10^{-2}$	$(488 \pm 5.4) \times 10^{-2}$	$(482 \pm 6.8) \times 10^{-2}$
99Tc	$(618 \pm 36.4) \times 10^{-2}$	$(618 \pm 5.6) \times 10^{-2}$	$(488 \pm 4.3) \times 10^{-2}$	$(621 \pm 8.7) \times 10^{-2}$
106Ru	$(418 \pm 6.9) \times 10^{-2}$	$(419 \pm 9.2) \times 10^{-2}$	$(434 \pm 10.0) \times 10^{-2}$	$(435 \pm 8.7) \times 10^{-2}$
106Rh	$(418 \pm 6.9) \times 10^{-2}$	$(419 \pm 9.2) \times 10^{-2}$	$(434 \pm 10.0) \times 10^{-2}$	$(435 \pm 8.7) \times 10^{-2}$
125Sb	$(20.7 \pm 3.8) \times 10^{-2}$	$(11.7 \pm 1.5) \times 10^{-2}$	$(11.1 \pm 1.9) \times 10^{-2}$	$(11.2 \pm 0.9) \times 10^{-2}$
126Sn	$(30.9 \pm 4.4) \times 10^{-2}$	$(26.4 \pm 4.7) \times 10^{-2}$	$(29.2 \pm 0.4) \times 10^{-2}$	$(19.9 \pm 1.6) \times 10^{-2}$
126mSb	$(30.9 \pm 4.4) \times 10^{-2}$	$(30.6 \pm 8.7) \times 10^{-3}$	$(47.4 \pm 11.7) \times 10^{-2}$	$(20.1 \pm 1.6) \times 10^{-2}$
126Sb	$(48.5 \pm 7.0) \times 10^{-3}$	$(22.2 \pm 7.1) \times 10^{-3}$	$(34.4 \pm 9.8) \times 10^{-4}$	$(29.5 \pm 2.4) \times 10^{-3}$
134Cs	$(5.6 \pm 2.0) \times 10^{-4}$	$(6.7 \pm 1.8) \times 10^{-4}$	$(5.6 \pm 1.5) \times 10^{-4}$	$(6.7 \pm 4.3) \times 10^{-4}$
137Cs	$(651 \pm 52.3) \times 10^{-2}$	$(659 \pm 8.0) \times 10^{-2}$	$(658 \pm 8.0) \times 10^{-2}$	$(661 \pm 3.3) \times 10^{-2}$
137mBa	$(616 \pm 11.7) \times 10^{-2}$	$(622 \pm 9.1) \times 10^{-2}$	$(622 \pm 9.1) \times 10^{-2}$	$(626 \pm 3.1) \times 10^{-2}$
144Ce	$(375 \pm 5.2) \times 10^{-2}$	$(375 \pm 3.0) \times 10^{-2}$	$(376 \pm 3.4) \times 10^{-2}$	$(374 \pm 2.6) \times 10^{-2}$
144mPr	$(56.7 \pm 0.8) \times 10^{-3}$	$(52.4 \pm 6.2) \times 10^{-3}$	$(52.1 \pm 5.6) \times 10^{-3}$	$(19.0 \pm 0.5) \times 10^{-3}$
144Pr	$(375 \pm 5.2) \times 10^{-2}$	$(380 \pm 3.0) \times 10^{-2}$	$(376 \pm 3.4) \times 10^{-2}$	$(374 \pm 1.9) \times 10^{-2}$
147Pm	$(205 \pm 0.2) \times 10^{-2}$	$(204 \pm 3.9) \times 10^{-2}$	$(204 \pm 3.9) \times 10^{-2}$	$(200 \pm 4.0) \times 10^{-2}$
154Eu	$(2.8 \pm 1.0) \times 10^{-5}$	$(4.9 \pm 1.3) \times 10^{-5}$	$(6.3 \pm 1.6) \times 10^{-6}$	$(2.8 \pm 1.8) \times 10^{-5}$

Table 11 Independent thermal fission yield data due to ^{235}U (%)

Nuclide	Evaluated library				
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF
85Kr	$(6.0 \pm 2.2) \times 10^{-3}$	$(4.9 \pm 1.8) \times 10^{-3}$	$(1.5 \pm 0.6) \times 10^{-3}$	$(6.0 \pm 2.2) \times 10^{-3}$	$(5.9 \pm 0.9) \times 10^{-3}$
89Sr	$(2.7 \pm 0.9) \times 10^{-3}$	$(2.2 \pm 0.8) \times 10^{-3}$	$(1.2 \pm 0.5) \times 10^{-2}$	$(1.8 \pm 1.1) \times 10^{-2}$	$(1.8 \pm 1.1) \times 10^{-2}$
90Sr	$(3.6 \pm 1.3) \times 10^{-2}$	$(3.1 \pm 1.8) \times 10^{-2}$	$(1.1 \pm 0.4) \times 10^{-1}$	$(7.4 \pm 0.4) \times 10^{-2}$	$(7.4 \pm 0.4) \times 10^{-2}$
90Y	$(8.2 \pm 3.1) \times 10^{-6}$	$(5.7 \pm 2.1) \times 10^{-6}$	$(1.3 \pm 0.5) \times 10^{-4}$	$(4.5 \pm 2.9) \times 10^{-6}$	$(4.5 \pm 2.9) \times 10^{-6}$
91Y	$(1.1 \pm 0.4) \times 10^{-4}$	$(8.6 \pm 3.1) \times 10^{-5}$	$(3.5 \pm 1.2) \times 10^{-4}$	$(1.7 \pm 1.1) \times 10^{-4}$	$(1.6 \pm 1.1) \times 10^{-4}$
95Zr	$(3.8 \pm 1.4) \times 10^{-2}$	$(3.5 \pm 1.3) \times 10^{-2}$	$(1.0 \pm 0.4) \times 10^{-1}$	$(1.3 \pm 0.2) \times 10^{-1}$	$(1.3 \pm 0.2) \times 10^{-1}$
95mNb	$(5.4 \pm 2.0) \times 10^{-6}$	$(4.1 \pm 1.5) \times 10^{-6}$	$(5.1 \pm 1.9) \times 10^{-5}$	$(2.5 \pm 1.6) \times 10^{-5}$	–
95Nb	$(2.3 \pm 0.9) \times 10^{-5}$	$(1.8 \pm 0.6) \times 10^{-5}$	$(2.2 \pm 0.8) \times 10^{-4}$	$(1.1 \pm 0.7) \times 10^{-4}$	$(2.5 \pm 1.6) \times 10^{-5}$
99Tc	$(3.5 \pm 1.3) \times 10^{-7}$	$(2.9 \pm 1.1) \times 10^{-7}$	(0 ± 0)	$(1.2 \pm 0.8) \times 10^{-7}$	$(2.9 \pm 1.8) \times 10^{-8}$
106Ru	$(2.6 \pm 1.2) \times 10^{-6}$	$(2.8 \pm 1.1) \times 10^{-6}$	$(5.4 \pm 4.3) \times 10^{-3}$	$(9.1 \pm 5.8) \times 10^{-7}$	$(9.1 \pm 5.8) \times 10^{-7}$
106Rh	$(3.4 \pm 1.6) \times 10^{-14}$	(0 ± 0)	$(5.3 \pm 2.4) \times 10^{-7}$	(0 ± 0)	0
125Sb	$(6.8 \pm 2.5) \times 10^{-5}$	$(7.2 \pm 2.6) \times 10^{-4}$	$(3.4 \pm 1.2) \times 10^{-4}$	$(2.7 \pm 2.7) \times 10^{-5}$	$(2.7 \pm 1.8) \times 10^{-5}$
126Sn	$(3.9 \pm 0.7) \times 10^{-2}$	$(4.0 \pm 0.6) \times 10^{-2}$	$(1.7 \pm 0.5) \times 10^{-2}$	$(4.5 \pm 2.9) \times 10^{-2}$	$(4.4 \pm 2.8) \times 10^{-2}$
126mSb	(0 ± 0)	$(1.7 \pm 0.6) \times 10^{-3}$	$(2.2 \pm 0.7) \times 10^{-4}$	$(8.6 \pm 5.5) \times 10^{-4}$	–
126Sb	$(5.7 \pm 2.1) \times 10^{-4}$	$(2.4 \pm 0.8) \times 10^{-3}$	$(3.0 \pm 0.1) \times 10^{-4}$	$(6.5 \pm 4.2) \times 10^{-4}$	$(8.6 \pm 5.5) \times 10^{-4}$
134Cs	$(1.7 \pm 0.6) \times 10^{-5}$	$(7.0 \pm 2.6) \times 10^{-6}$	$(1.0 \pm 0.4) \times 10^{-6}$	$(3.9 \pm 2.5) \times 10^{-6}$	$(3.9 \pm 2.5) \times 10^{-6}$
137Cs	$(8.7 \pm 3.1) \times 10^{-2}$	$(7.2 \pm 2.6) \times 10^{-2}$	$(8.1 \pm 2.9) \times 10^{-2}$	$(6.0 \pm 0.7) \times 10^{-2}$	$(6.0 \pm 0.7) \times 10^{-2}$
137mBa	$(2.1 \pm 0.7) \times 10^{-4}$	$(1.3 \pm 0.5) \times 10^{-4}$	$(4.9 \pm 1.8) \times 10^{-4}$	$(1.3 \pm 0.9) \times 10^{-4}$	–
144Ce	$(3.9 \pm 1.5) \times 10^{-2}$	$(3.5 \pm 1.3) \times 10^{-2}$	$(4.1 \pm 1.5) \times 10^{-2}$	$(3.5 \pm 2.2) \times 10^{-2}$	$(3.5 \pm 2.2) \times 10^{-2}$
144mPr	$(2.2 \pm 0.8) \times 10^{-5}$	$(1.5 \pm 0.6) \times 10^{-5}$	$(6.7 \pm 2.5) \times 10^{-7}$	$(1.3 \pm 0.8) \times 10^{-5}$	–
144Pr	$(2.5 \pm 0.9) \times 10^{-6}$	$(1.7 \pm 0.6) \times 10^{-6}$	$(7.5 \pm 2.8) \times 10^{-8}$	$(1.4 \pm 0.9) \times 10^{-6}$	$(1.3 \pm 0.8) \times 10^{-5}$
147Pm	$(6.4 \pm 2.3) \times 10^{-9}$	$(3.5 \pm 1.2) \times 10^{-9}$	$(3.5 \pm 1.2) \times 10^{-9}$	$(2.5 \pm 1.6) \times 10^{-9}$	$(2.5 \pm 1.6) \times 10^{-9}$
154Eu	$(1.7 \pm 0.6) \times 10^{-7}$	$(1.0 \pm 0.5) \times 10^{-7}$	$(3.0 \pm 1.3) \times 10^{-9}$	$(9.7 \pm 6.2) \times 10^{-8}$	$(9.7 \pm 6.2) \times 10^{-8}$

Table 12 Independent thermal fission yield data due to ^{239}Pu (%)

Nuclide	Evaluated library				
	JEF2.2	JEFF3.1.1	JEFF3.3	ENDF/B-VIII.0	ENSDF
85Kr	$(1.1 \pm 0.4) \times 10^{-2}$	$(1.2 \pm 0.4) \times 10^{-2}$	$(1.4 \pm 0.5) \times 10^{-2}$	$(1.0 \pm 0.6) \times 10^{-2}$	$(2.4 \pm 1.5) \times 10^{-3}$
89Sr	$(5.8 \pm 2.1) \times 10^{-3}$	$(7.0 \pm 2.6) \times 10^{-3}$	$(1.1 \pm 0.4) \times 10^{-2}$	$(1.5 \pm 1.0) \times 10^{-2}$	$(1.5 \pm 1.0) \times 10^{-2}$
90Sr	$(5.0 \pm 1.8) \times 10^{-2}$	$(5.7 \pm 2.1) \times 10^{-2}$	$(10.4 \pm 3.5) \times 10^{-2}$	$(9.7 \pm 4.4) \times 10^{-2}$	$(9.7 \pm 4.4) \times 10^{-2}$
90Y	$(4.2 \pm 1.6) \times 10^{-5}$	$(6.3 \pm 2.3) \times 10^{-5}$	$(7.7 \pm 2.8) \times 10^{-5}$	$(10.0 \pm 6.2) \times 10^{-5}$	$(9.6 \pm 6.2) \times 10^{-5}$
91Y	$(4.1 \pm 1.5) \times 10^{-4}$	$(5.3 \pm 1.9) \times 10^{-4}$	$(5.5 \pm 1.9) \times 10^{-4}$	$(1.2 \pm 0.8) \times 10^{-3}$	$(1.2 \pm 0.8) \times 10^{-3}$
95Zr	$(1.1 \pm 0.4) \times 10^{-1}$	$(1.3 \pm 0.5) \times 10^{-1}$	$(1.7 \pm 0.6) \times 10^{-1}$	$(1.3 \pm 0.8) \times 10^{-1}$	$(1.3 \pm 0.8) \times 10^{-1}$
95mNb	$(5.4 \pm 2.0) \times 10^{-5}$	$(8.4 \pm 3.1) \times 10^{-5}$	$(9.1 \pm 3.3) \times 10^{-5}$	$(1.3 \pm 0.8) \times 10^{-4}$	–
95Nb	$(2.3 \pm 0.9) \times 10^{-5}$	$(3.6 \pm 1.3) \times 10^{-4}$	$(3.9 \pm 1.4) \times 10^{-4}$	$(5.7 \pm 3.6) \times 10^{-4}$	$(1.3 \pm 0.8) \times 10^{-4}$
99Tc	$(6.7 \pm 2.4) \times 10^{-6}$	$(1.3 \pm 0.5) \times 10^{-5}$	$(1.5 \pm 0.5) \times 10^{-6}$	$(1.2 \pm 0.8) \times 10^{-5}$	$(1.5 \pm 0.5) \times 10^{-6}$
106Ru	$(3.1 \pm 1.1) \times 10^{-1}$	$(3.0 \pm 1.0) \times 10^{-1}$	$(5.3 \pm 1.4) \times 10^{-1}$	$(3.2 \pm 1.0) \times 10^{-1}$	$(3.2 \pm 1.0) \times 10^{-1}$
106Rh	$(4.3 \pm 1.5) \times 10^{-4}$	$(8.2 \pm 3.0) \times 10^{-4}$	$(2.2 \pm 0.7) \times 10^{-3}$	$(2.2 \pm 1.4) \times 10^{-4}$	$(2.2 \pm 1.4) \times 10^{-4}$
125Sb	$(8.5 \pm 3.3) \times 10^{-4}$	$(1.3 \pm 0.4) \times 10^{-2}$	$(2.4 \pm 0.9) \times 10^{-3}$	$(6.6 \pm 4.2) \times 10^{-4}$	$(6.6 \pm 4.2) \times 10^{-4}$
126Sn	$(2.3 \pm 0.4) \times 10^{-1}$	$(2.0 \pm 0.4) \times 10^{-1}$	$(1.6 \pm 0.3) \times 10^{-1}$	$(1.7 \pm 0.3) \times 10^{-1}$	$(1.7 \pm 0.3) \times 10^{-1}$
126mSb	(0 ± 0)	$(0.1 \pm 0) \times 10^{-3}$	$(2.1 \pm 0.7) \times 10^{-3}$	$(1.2 \pm 0.7) \times 10^{-3}$	–
126Sb	$(5.3 \pm 2.1) \times 10^{-3}$	$(18 \pm 6.2) \times 10^{-3}$	$(2.8 \pm 1.0) \times 10^{-3}$	$(1.4 \pm 0.9) \times 10^{-3}$	–
134Cs	$(4.8 \pm 1.7) \times 10^{-4}$	$(3.9 \pm 1.4) \times 10^{-4}$	$(3.2 \pm 1.2) \times 10^{-4}$	$(3.4 \pm 2.1) \times 10^{-4}$	$(3.3 \pm 2.1) \times 10^{-4}$
137Cs	$(4.3 \pm 1.6) \times 10^{-1}$	$(4.6 \pm 1.6) \times 10^{-1}$	$(4.7 \pm 1.7) \times 10^{-1}$	$(6.0 \pm 1.0) \times 10^{-1}$	$(6.0 \pm 1.0) \times 10^{-1}$
137mBa	$(3.1 \pm 1.1) \times 10^{-3}$	$(3.8 \pm 1.4) \times 10^{-3}$	$(5.2 \pm 1.9) \times 10^{-3}$	$(4.5 \pm 2.9) \times 10^{-3}$	–
144Ce	$(1.4 \pm 0.5) \times 10^{-1}$	$(1.6 \pm 0.6) \times 10^{-1}$	$(1.9 \pm 0.6) \times 10^{-1}$	$(1.2 \pm 0.7) \times 10^{-1}$	$(1.2 \pm 0.7) \times 10^{-1}$
144mPr	$(3.8 \pm 1.4) \times 10^{-4}$	$(5.7 \pm 2.1) \times 10^{-4}$	$(1.7 \pm 0.6) \times 10^{-4}$	$(3.3 \pm 2.1) \times 10^{-4}$	–
144Pr	$(4.3 \pm 1.6) \times 10^{-5}$	$(6.4 \pm 2.4) \times 10^{-5}$	$(1.9 \pm 0.7) \times 10^{-5}$	$(3.7 \pm 2.3) \times 10^{-5}$	$(3.3 \pm 2.1) \times 10^{-4}$
147Pm	$(3.5 \pm 1.3) \times 10^{-7}$	$(7.7 \pm 2.8) \times 10^{-7}$	$(7.7 \pm 2.8) \times 10^{-7}$	$(6.5 \pm 4.2) \times 10^{-7}$	$(6.5 \pm 1.5) \times 10^{-7}$
154Eu	$(1.5 \pm 0.5) \times 10^{-5}$	$(2.6 \pm 0.9) \times 10^{-5}$	$(3.3 \pm 0.1) \times 10^{-5}$	$(1.4 \pm 0.9) \times 10^{-5}$	$(1.4 \pm 0.9) \times 10^{-5}$

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