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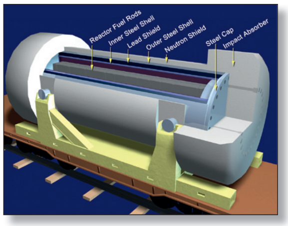
Burn-up Credit Criticality Safety Benchmark – Phase VII

UO_2 Fuel: Study of Spent Fuel Compositions for Long-term Disposal



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Burn-up Credit Criticality Safety Benchmark Phase VII

UO_2 Fuel: Study of Spent Fuel Compositions for Long-term Disposal

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A report by the Expert Group on Burn-up Credit Criticality
NEA Nuclear Science Committee
Working Party on Nuclear Criticality Safety

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Cover photo: Diagram of a spent fuel cask, United States (NEI).

Foreword

Under the auspices of the NEA Nuclear Science Committee (NSC), the Working Party on Nuclear Criticality Safety (WPNCS) was established to co-ordinate scientific activities relevant to criticality safety. Specific areas of interest include investigations of static and transient configurations during fuel fabrication, transport and storage.

The WPNCS Expert Group on Burn-up Credit (EGBUC) was established in 1991 to address scientific and technical issues connected to the use of burn-up credit in nuclear fuel cycle operations. Criticality safety methodologies that take into account a reduction in the reactivity of irradiated fuel due to fuel burn-up are commonly referred to as *taking burn-up credit*. This reduction of reactivity with fuel burn-up is mostly due to the net reduction of fissile nuclides and the production of actinide and fission-product neutron absorbers.

Due to the decay of unstable nuclides, fuel reactivity will continue to vary as a function of time after spent nuclear fuel (SNF) is discharged from a reactor. The vast majority of the published burn-up-credit-related studies have addressed the criticality safety of SNF storage and transportation for a period of time that is extremely short (typically less than 100 years) as compared to the time frame of interest to long-term disposal.

Accurate predictions of the concentrations of long-lived radionuclides in SNF, which represent a significant potential hazard to human beings and to the environment over a very long period, are necessary for radiological dose assessments. Hence, the Burn-up Credit Criticality Safety Benchmark Phase VII proposed to study the ability of existing computer codes and associated nuclear data to predict spent fuel isotopic compositions and corresponding k_{eff} values in a cask configuration over 10^6 years from discharge. The spent fuel considered is standard pressurised-water-reactor (PWR) UO_2 fuel of 4.5 wt% initial enrichment and 50 GWd/MTU burn-up. This report describes the results of the benchmark.

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Executive summary

The purpose of Burn-up Credit Criticality Safety Benchmark Phase VII, entitled UO_2 Fuel: Study of Spent Fuel Compositions for Long-Term Disposal, was to study the ability of relevant computer codes and associated nuclear data to predict spent nuclear fuel (SNF) isotopic compositions and corresponding effective neutron multiplication factor (k_{eff}) values in a generic spent fuel cask configuration over the time duration relevant to SNF disposal. The expected outcome of the benchmark exercise includes an improved understanding relative to potential differences in international nuclear data sets and a better understanding and/or confidence in the ability to predict k_{eff} and the concentrations of radiologically important nuclides for time frames relevant to long-term storage and disposal of SNF.

The Phase VII benchmark specified the following: (1) the discharged fuel composition of a representative pressurised-water-reactor (PWR) UO_2 fuel assembly of 4.5 wt% initial enrichment and 50 GWd/MTU burn-up including actinide and fission product nuclides important to burn-up credit criticality safety analyses and radiological dose assessments as well as their precursors (113 total nuclides) for use as the initial fuel composition in decay calculations; (2) the geometry characteristics and structural material compositions of a generic spent fuel cask loaded with 21 PWR UO_2 17×17 fuel assemblies for use in criticality calculations. The benchmark requested calculations of decayed fuel compositions and corresponding k_{eff} values for 30 post-irradiation time steps, out to 10^6 years. The cask model assumed intact fuel assemblies throughout the time interval. Forty-four structural material activation product, fission product, and actinide nuclides were selected for comparison based on their important contributions to radiation dose from nuclear waste repositories. The set of nuclides important to radiological dose assessments included ^{14}C, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{79}Se, ^{93}Zr, ^{90}Sr, ^{93m}Nb, ^{94}Nb, ^{93}Mo, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{126}Sb, ^{126m}Sb, ^{129}I, ^{135}Cs, ^{137}Cs, ^{151}Sm, ^{210}Pb, ^{226}Ra, ^{228}Ra, ^{227}Ac, ^{229}Th, ^{230}Th, ^{232}Th, ^{231}Pa, ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{245}Cm, and ^{246}Cm. Two different sets of nuclides important to burn-up credit criticality safety analyses consisting of either major actinide nuclides (^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am) or actinide and fission product nuclides (^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{143}Nd, ^{145}Nd, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{151}Eu, ^{153}Eu, and ^{155}Gd) were specified for use in criticality calculations.

Contributions from 15 organisations in 10 countries were submitted to the Phase VII benchmark. The participating decay codes included ACAB-2008, CINDER 90, DARWIN 2.0 and 2.1, ORIGEN-S in SCALE 5.1, 6.0, and 6.1 (beta), ORIGEN2.2-UPJ, ORIGEN-X-2008, PHOENIX 1.0.0a (beta), and TIBSO. The primary sources of the associated decay data were the ENDF/B-IV, -VI and -VII, ENSDF, JEF2, JEFF-3.1, and JENDL-3.3 libraries. In addition to the variety of decay data libraries, the participating decay codes used numerical solutions of decay chain equations based on the matrix exponential method (e.g. ORIGEN-based decay codes such as ORIGEN-S, ORIGEN2.2-UPJ, ORIGEN-X-2008, and ACAB) and on the fourth-order Runge-Kutta numerical method (e.g. PHOENIX), and the analytical solution of the linearised Bateman decay chains (e.g. CINDER 90). The criticality codes used by the participants included the Monte Carlo codes KENO-V.a in SCALE 6.0 and 6.1 (beta), KENO-VI in SCALE 5.1, MCNP 4C2 and 5, MCNPX 2-4 and 2-5, MORET 4.B.2 in CRISTAL V1.0, and MORET5 with either multi-group or continuous-energy nuclear cross-section data based on ENDF/B-V, -VI, and -VII, JEF2.2, JEFF-3.1.1, and JENDL-3.3. The relative standard deviation (RSD) of the calculated values and plots of the relative difference between the calculated and the mean values as a function of decay time were useful in identifying differences in nuclear data and code-specific numerical approximations.

The concentrations of nuclides ^{90}Sr, ^{137}Cs, ^{151}Sm, ^{232}U, ^{238}Pu, ^{241}Pu, and ^{242m}Am decrease to insignificant levels after approximately 10^3 years from fuel discharge; the concentrations of nuclides ^{14}C, ^{93}Mo, ^{240}Pu, ^{241}Am, ^{243}Am, ^{245}Cm, and ^{246}Cm decrease to negligible levels after approximately 10^5 years from fuel discharge. However, the concentrations of nuclides ^{151}Eu, ^{210}Pb, ^{226}Ra, ^{228}Ra, ^{227}Ac,

^{229}Th, ^{230}Th, ^{232}Th, ^{231}Pa, and ^{233}U significantly increase with decay time due to precursor decay chains contributing to the formation of those nuclides. The concentrations of the long-lived major burn-up credit actinide nuclides ^{235}U and ^{236}U slightly increase after approximately 10^4 years from fuel discharge primarily due to alpha decay of ^{239}Pu and ^{240}Pu, respectively. Differences observed in the calculated atom densities of nuclides important to burn-up credit criticality analyses and radiological dose assessments may be attributed to (1) different decay data, (2) the ability of the decay codes to consider relevant precursor decay chains contributing to the formation of a nuclide of interest, and (3) approximations related to the number of time steps allowed by the code that impacted the accuracy with which contributions from short-lived parents were calculated. The spread of the decay calculation results varied considerably depending on the nuclide and decay time. The decay calculation results for major actinide nuclides ^{235}U, ^{236}U, ^{238}U, and ^{239}Pu were practically identical. For many nuclides, correlations were established between the half-life and/or branching ratio values associated with the evaluated decay libraries and the observed trends of nuclide concentration values relative to the mean values. A review of the decay data in the ENDF/B-VII.0, JEFF-3.1, ENDF/B-VI.8, JEF-2, ENSDF, and JENDL-3.3 libraries identified a series of nuclides for which significant differences exist among the decay data evaluations. Nuclides most impacted by different half-life values associated with those libraries were ^{14}C, ^{41}Ca, ^{59}Ni, ^{79}Se, ^{90}Sr, ^{94}Nb, ^{93}Mo, ^{99}Tc, ^{126}Sn, ^{151}Sm, ^{155}Eu, ^{229}Th, ^{232}U, ^{236}Np, ^{236}Pu, and ^{246}Cm. Different branching ratio values for the beta decay transition of ^{93}Zr to ^{93m}Nb affected the calculated ^{93m}Nb densities. Differences between the earlier ENDF/B-IV decay data and the decay data in the more recent evaluations affected the calculated atom densities for nuclides ^{41}Ca, ^{59}Ni, ^{93m}Nb, ^{228}Ra, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, ^{242m}Am and ^{243}Am.

The k_{eff} values for the generic spent fuel cask continuously decrease until approximately 100 years after fuel discharge and then increase, with increasing time reaching a peak value at approximately 2.5×10^5 years after fuel discharge. The decrease in k_{eff} for the first 100 years after fuel discharge is caused primarily by the decay of the fissile nuclide ^{241}Pu ($T_{1/2}$ = 14.29 years) to ^{241}Am (neutron absorber), whereas the increase in fuel reactivity after this time is caused by the decay of neutron absorber nuclides ^{238}Pu ($T_{1/2}$ = 87.7 years), ^{240}Pu ($T_{1/2}$ = 6 561 years), ^{241}Am ($T_{1/2}$ = 432.6 years), and ^{243}Am ($T_{1/2}$ = 7 370 years). The dispersion of the participants' k_{eff} results varied depending on the decay time. The average value and the relative standard deviation of the k_{eff} results for fresh fuel were 1.1486 and 0.22%, respectively. The calculated k_{eff} values for actinide-only fuel compositions had a maximum RSD of 0.47% at 10^5 years; the maximum RSD of the k_{eff} values for actinide and fission product fuel compositions was 0.41% at 10^6 years.

The impact of cross-section data uncertainties on the k_{eff} values for fuel compositions containing actinide and fission product nuclides important to burn-up credit was evaluated in this report. Energy and region integrated k_{eff} sensitivities to nuclide total and reaction-specific cross sections and the relative uncertainty in k_{eff} due to cross-section covariance data were calculated using the TSUNAMI sequence in SCALE. The sensitivity of k_{eff} to a particular nuclide-reaction pair macroscopic cross section, referred to as the sensitivity coefficient, provides a measure of the first-order effect of perturbations in the nuclear reaction for the nuclide on k_{eff}. The uncertainties associated with ^{239}Pu, ^{235}U, and ^{238}U cross-section data had a dominating effect on the uncertainty in k_{eff}. The relative uncertainty in k_{eff} due to cross-section covariance data, which varied from 0.48% (10^5 years) to 0.76% (10^2 years), was slightly greater than the maximum RSD of the k_{eff} values (0.41%) calculated by the participants. Hence, the small variability of the k_{eff} benchmark calculation results may be predominantly attributed to the criticality calculation methods and cross-section data.

1. Introduction

This report describes the results of Burn-up Credit Criticality Safety Benchmark Phase VII [1] conducted by the Expert Group on Burn-up Credit Criticality Safety, which is co-ordinated by the Working Party on Nuclear Criticality Safety within the Organisation for Economic Co-operation and Development (OECD) Nuclear Energy Agency (NEA). The purpose of the Phase VII benchmark was to study the ability of relevant computer codes and associated nuclear data to predict spent fuel isotopic compositions and corresponding effective neutron multiplication factor (k_{eff}) values in a cask configuration over the time duration relevant to spent nuclear fuel (SNF) long-term storage and disposal. The objective of the benchmark was to improve understanding and confidence in the ability to predict k_{eff} and the concentrations of radiologically important nuclides for time frames relevant to long-term storage and disposal of spent nuclear fuel.

The concept of taking credit for a reduction in reactivity due to fuel burn-up is commonly referred to as *burn-up credit*. The reduction in reactivity that occurs with fuel burn-up is due to the change in concentration (net reduction) of fissile nuclides and the production of actinide and fission-product neutron absorbers. Fuel reactivity also continues to vary as a function of time after the SNF is discharged from a reactor due to the decay of unstable nuclides. The vast majority of the published burn-up-credit-related studies have addressed the criticality safety of SNF storage and transportation for a period of time that is extremely short (typically less than 100 years) as compared to the time frame of interest to long-term disposal. Therefore, the ability of the existing decay and criticality codes to accurately predict decay fuel compositions and k_{eff} values for burn-up credit applications has been primarily evaluated for decay times less than 100 years. Accurate predictions of the concentrations of long-lived radionuclides in SNF, which represent a significant hazard to human beings and to the environment over a very long period of time, are necessary for radiological dose assessments. Hence, the Burn-up Credit Criticality Safety Benchmark Phase VII proposed to study the ability of existing computer codes and associated nuclear data to predict spent fuel isotopic compositions and corresponding k_{eff} values in a cask configuration over 10^6 years from fuel discharge (refer to Appendix A for complete benchmark specifications).

The benchmark was divided into two sets of calculations: (1) decay calculations using nuclide concentrations specified by the benchmark for discharged pressurised-water-reactor (PWR) UO_2 fuel of 4.5 wt% initial enrichment and 50 GWd/MTU burn-up; (2) criticality calculations using the predicted time-dependent compositions for actinide and fission product nuclides important to burn-up credit in a generic spent fuel cask configuration specified by the benchmark. The initial fuel composition specified by the benchmark included nuclides important to burn-up credit criticality safety analyses and to radiological dose assessments as well as their precursors (113 total nuclides). The benchmark requested fuel decay compositions and corresponding k_{eff} values to be calculated for 30 post-irradiation time steps, out to 10^6 years. Two sets of nuclides important to burn-up credit criticality analyses were specified: one set consisted of 11 major actinide nuclides, and the other set included 14 major and minor actinide nuclides and 16 fission product nuclides.

Contributions from 15 organisations in 10 countries were submitted to the Phase VII benchmark. The organisations participating in the benchmark, the decay and criticality computer codes, and the nuclear data used by the participants are presented in Chapter 2. The time-dependent fuel compositions calculated by the participants along with an analysis of the decay calculation results are presented in Chapter 3. The time-dependent k_{eff} values obtained by the participants for the generic spent fuel cask model with fuel compositions consisting of either major actinide nuclides or actinide and fission product nuclides important to burn-up credit criticality safety analyses, as well as a cross-section sensitivity and uncertainty analysis performed by the authors of this report, are presented in Chapter 4. Conclusions on the Phase VII benchmark calculation results and the references cited in the current report are provided in the last two sections. Appendix A contains the complete specifications of the Phase VII benchmark. Summary information provided by the participants about the computational methods and nuclear data libraries used in their benchmark calculations is presented in Appendix B. Appendix C presents additional analyses provided by the Spanish participants.

2. Computer codes and nuclear data

Contributions from 15 organisations in 10 countries were submitted to the Phase VII benchmark. The participating decay codes included ACAB-2008 [2], CINDER 90 [3], DARWIN 2.0 and 2.1 [4], ORIGEN-S in SCALE 5.1, 6.0 [5], and 6.1 (beta), ORIGEN2.2-UPJ [6], ORIGEN-X-2008 [7], PHOENIX 1.0.0a (beta) [8], and TIBSO [9]. The source of the associated decay data was either the United States Evaluated Nuclear Data File (ENDF)/B-IV,-VI [10], and VII [11], NEA Joint Evaluated Fission and Fusion File (JEFF)-3.1 [12], Joint European File (JEF)-2 [13], Evaluated Nuclear Structure Data File (ENSDF) [14], or the Japan Evaluated Nuclear Data Library (JENDL)-3.3 [15]. In addition to the variety of decay data libraries, the participating decay codes used numerical solutions of decay chain equations based on the matrix exponential method (e.g. ORIGEN-S, ORIGEN2.2-UPJ, ORIGEN-X-2008, and ACAB) and on the fourth-order Runge-Kutta numerical method (e.g. PHOENIX), and the analytical solution of the linearised Bateman decay chains (e.g. CINDER 90). The criticality codes used by the participants included the Monte Carlo codes KENO-V.a in SCALE 6.0 and 6.1 (beta), KENO-VI in SCALE 5.1, MCNP 4C2 and 5 [16], MCNPX 2-4 and 2-5 [16], MORET 4.B.2 in CRISTAL V1.0 [17], and MORET 5 [18] with either continuous or multi-group cross-section data based on ENDF/B-V, -VI, and -VII, JEF-2.2, JEFF-3.1.1, and JENDL-3.3.

The organisations participating in the benchmark Phase VII exercise and the decay codes and data libraries used by the participants are presented in Table 1. A detailed description of the participants' methods, data, and assumptions are included in Appendix B.

Table 1. Participating organisations and decay analysis methods

Country	Organisation	Decay code	Decay data library[a]	Criticality code	Nuclear cross-section library
Slovak Republic	Nuclear Power Plant Research Institute Trnava Inc, VUJE	SCALE 5.1/ORIGEN-S	ENDF/B-VI	SCALE 5.1/KENO VI	ENDF/B-V, 44 energy groups (CENTRM)
United States	Oak Ridge National Laboratory	SCALE 6.1/ ORIGEN-S (beta)	ENDF/B-VII	SCALE 6.1/KENO V.a (beta)	ENDF/B-VII.0, continuous energy
Japan	Japan Atomic Energy Agency	ORIGEN2.2UPJ	ORLIBJ33[b]	MCNP-4C2	JENDL-3.3, continuous energy (NJOY99r2)
Sweden	E Mennerdahl Systems	SCALE 6.0/ORIGEN-S	ENDF/B-VI	SCALE 6.0/KENO V.a	ENDF/B-VII.0, continuous energy
Spain	DENIM/CSN/SEA Ingenieria	ACAB-2008	JEFF-3.1	MCNPX-2.5	JEFF-3.1.1, continuous energy (NJOY99.259)
		ACAB-2008	JEFF-3.1	MCNPX-2.4.0	ENDF/B-VI, continuous energy
		ACAB-2008	ENDF/B-VI	MCNPX-2.5	JEFF-3.1.1, continuous energy (NJOY99.259)
France	AREVA-TN International	DARWIN 2.1	JEF-2.2	CRISTAL V1.0 (APOLLO 2.5.4, MORET 4.B.2)	JEF-2.2, 172 energy groups
France	Institut de Radioprotection et de Sûreté Nucléaire (IRSN)	DARWIN 2.0	JEF-2	MORET 5	JEFF-3.1, continuous energy NJOY99.259 (ACE files)
		PHOENIX 1.0.0a (beta)	ORIGEN2.2 DECAY.LIB[c]	–	–
Germany	Gesellschaft für Anlagen- und Reaktorsicherheit mbH (GRS)	ORIGEN-X-2008	ENDF/B-VI	SCALE 6.0/KENO V.a	ENDF/B-VII.0, 238 energy groups
Czech Republic	Nuclear Research Institute at Rez	SCALE 6.0/ORIGEN-S	ENDF/B-VI	SCALE 6.0/KENO V.a	ENDF/B-VII.0, 238 energy groups
				SCALE 6.0/KENO V.a	ENDF/B-VII.0, continuous energy
Finland	VTT Technical Research Centre of Finland	SCALE 6.0/ORIGEN-S	ENDF/B-VI	MCNP5 1.40	ENDF/B-VII, continuous energy
Hungary	KFKI Atomic Energy Research Institute & Anandor Ltd.	SCALE 6.0/ORIGEN-S	ENDF/B-VI	MCNP5	ENDF/B-VI.2 and V
		TIBSO	JEF-2.2	MCNP5	ENDF/B-VI.2 and V
United States	Los Alamos National Laboratory	CINDER 90	ENDF/B-VI	–	–

[a] Some of the decay codes utilise decay data from more than one decay data sources (e.g. the primary source of the decay data in SCALE 6.0/ORIGEN-S is ENDF/B-VI, supplemented with data from ENSDF and JEF-2.2 where ENDF/B-VI data was missing). The primary source of the decay data is listed in the table.
[b] Refer to Appendix B.3 for detailed information.
[c] Decay data primarily from the ENDF/B-IV evaluations.

3. Decay calculation results and their analysis

This section presents the results of the benchmark decay calculations for each nuclide of interest. Forty-four structural material activation product, fission product, and actinide nuclides were selected for comparison based on their relevant contributions to radiation dose from nuclear waste repositories. The set of nuclides important to radiological dose assessment included ^{14}C, ^{36}Cl, ^{41}Ca, ^{59}Ni, ^{79}Se, ^{93}Zr, ^{90}Sr, ^{93m}Nb, ^{94}Nb, ^{93}Mo, ^{99}Tc, ^{107}Pd, ^{126}Sn, ^{126}Sb, ^{126m}Sb, ^{129}I, ^{135}Cs, ^{137}Cs, ^{151}Sm, ^{210}Pb, ^{226}Ra, ^{228}Ra, ^{227}Ac, ^{229}Th, ^{230}Th, ^{232}Th, ^{231}Pa, ^{232}U, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{245}Cm, and ^{246}Cm [19]. An additional 14 nuclides, the majority of which are stable fission products, were selected based on their importance to burn-up credit criticality safety analyses (refer to Table 96 for the list of burn-up credit nuclides).

The mean values of the calculated atom densities for the 58 nuclides are represented as a function of decay time in Figure 1. The burn-up credit nuclides are illustrated in Figure 1(a); additional nuclides important to radiation dose are illustrated in Figure 1(b). As seen in the figure, the concentrations of nuclides ^{90}Sr, ^{137}Cs, ^{151}Sm, ^{232}U, ^{238}Pu, ^{241}Pu, and ^{242m}Am decrease to insignificant levels after approximately 103 years from fuel discharge; the concentrations of nuclides ^{14}C, ^{93}Mo, ^{240}Pu, ^{241}Am, ^{243}Am, ^{245}Cm, and ^{246}Cm decrease to negligible levels after approximately 105 years from fuel discharge. However, the concentrations of nuclides ^{151}Eu, ^{210}Pb, ^{226}Ra, ^{228}Ra, ^{227}Ac, ^{229}Th, ^{230}Th, ^{232}Th, ^{231}Pa, and ^{233}U significantly increase with decay time due to precursor decay chains contributing to the formation of those nuclides. The concentrations of the long-lived major burn-up credit actinide nuclides ^{235}U and ^{236}U slightly increase after approximately 104 years from fuel discharge due to alpha decay of ^{239}Pu and ^{240}Pu, respectively. The concentrations of a series of stable fission product nuclides important to burn-up credit criticality safety analyses, including ^{95}Mo, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{143}Nd, ^{149}Sm, ^{151}Eu, and ^{155}Gd, increase after fuel discharge as a result of the beta decay of their precursors. The precursors of ^{95}Mo, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{143}Nd, and ^{149}Sm are short-lived radionuclides (e.g. ^{95}Nb, ^{103}Ru, ^{109}Pd, ^{133}I, ^{133}Xe, ^{143}Pr, ^{149}Pm, and ^{149}Nd), which completely decay within the first year from fuel discharge. However, ^{151}Eu and ^{155}Gd concentrations in discharged nuclear fuel continue to increase over a longer period of time due to ^{151}Sm ($T_{1/2}$ = 90 ± 8 years) and ^{155}Eu ($T_{1/2}$ = 4.753 ± 0.014 years) decay, respectively.

The time-dependent fuel compositions calculated by the participants, the decay data used, and an analysis of the results are presented in Sections 3.1 through 3.47 for each nuclide with varying atom densities. Those sections include figures showing the relative difference between the atom density obtained by each evaluated decay code/data library and the sample mean as a function of decay time, and tables presenting the half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0 and -VI.8 [20], JEFF-3.1 [12], JEF-2.2 [13], ORIGEN2.2-UPJ ORLIBJ3.3 [14] and [15], and ORIGEN2.2 DECAY.LIB [21] decay data libraries for nuclides of interest. To help in understanding the impact of precursor decay data on the calculated concentrations for affected nuclides (e.g. ^{210}Pb), additional figures are provided showing, as a function of decay time, the cumulative nuclide atom density and individual contributions from significant decay chains contributing to the formation of the nuclide of interest. Note that ORLIBJ3.3 decay data from references 14 and 15 only, which were readily available, were used in the analyses presented in this report (refer to Appendix B.3 for detailed information about the decay data used in the ORIGEN2.2-UPJ decay calculations). The decay data in the ORIGEN2.2 DECAY.LIB, which were used in PHOENIX 1.0.0a (beta) calculations, are primarily based on the ENDF/B-IV evaluations. The frequent use of the ENDF/B-VII values in the analyses of the decay calculation results was based on their ready availability; half-life values from other relevant evaluations are also provided for comparison purposes.

The following conversions were used to obtain half-life values in seconds for half-life values expressed in different time units e.g. [13 and 21]: 1 year = 31.556.926 seconds; 1 year = 365.2422 days [12]. A series of symbols were used throughout this document, as follows: $T_{1/2}$ denotes half-life, α denotes decay by alpha-particle emission, β^- denotes decay by beta-particle emission, and IT denotes isomeric transition.

Standard deviation of the calculated values and plots of the relative difference between the calculated and the mean values as a function of decay time were useful in identifying the impact of different nuclear data and code-specific numerical approximations. The sample mean, $\overline{X}$, standard deviation, SD, and relative standard deviation, RSD, of a parameter of interest (e.g. atom density, k_{eff}) were calculated as shown in Equation (1), (2), and (3), respectively, where X_i is the result of calculation i and N is the number of calculations,

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} X_i \,, \tag{1}$$

$$SD = \sqrt{\sum_{i=1}^{N}(X_i - \overline{X})^2 \Big/ N} \,, \tag{2}$$

$$RSD = SD \big/ \overline{X} \,. \tag{3}$$

Figure 1. Atom density as a function of time for nuclides important to burn-up credit criticality safety analyses and radiological dose assessments

(a)

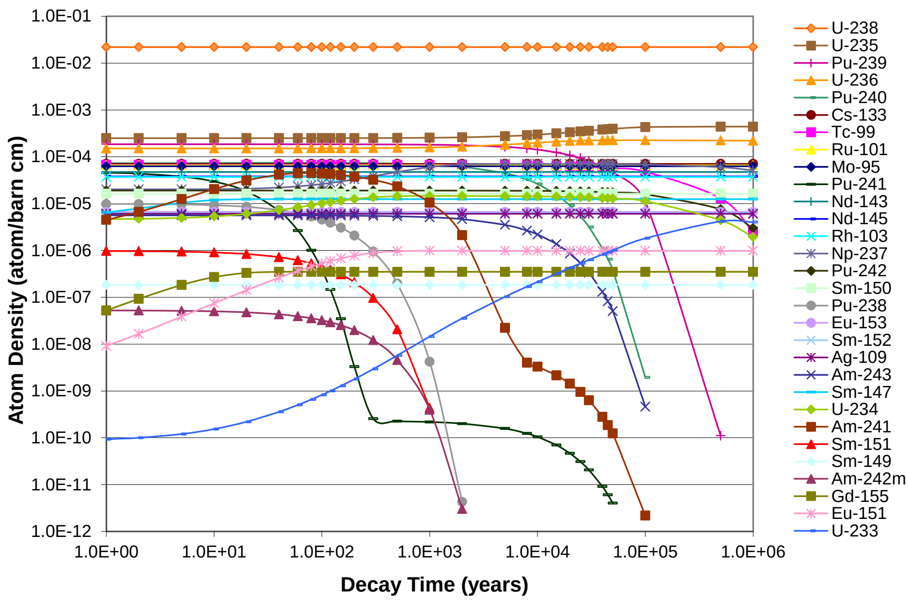

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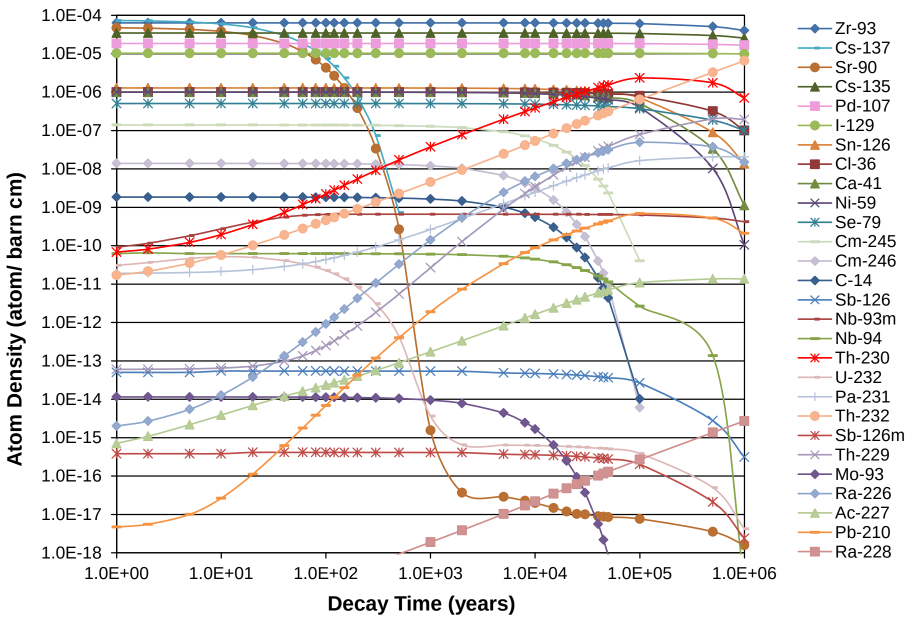
Figure 1. Atom density as a function of time for nuclides important to burn-up credit criticality safety analyses and radiological dose assessments *(continued)*

(b)



Note: All nuclides in Figure 1(a) are important to burn-up credit; nuclides ^{99}Tc, ^{151}Sm, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, and ^{243}Am in Figure 1(a) are also considered important to radiological dose assessments; all nuclides in Figure 1(b) are important to radiological dose assessments.

3.1. Time-dependent ^{14}C atom densities

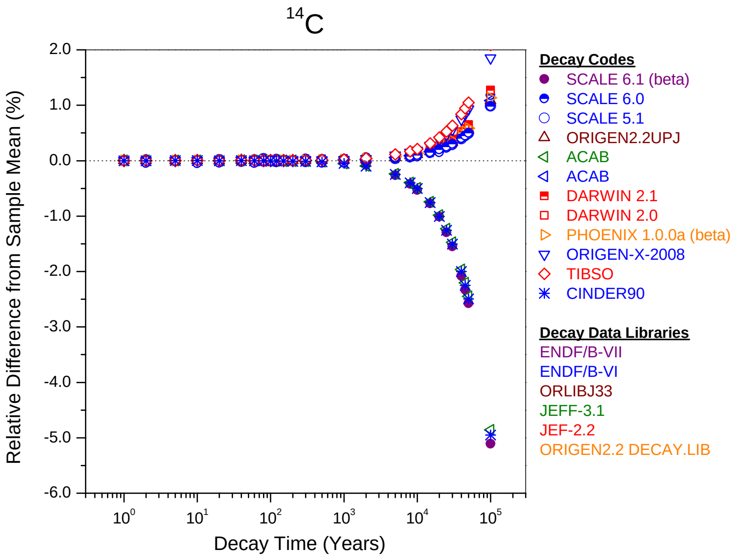
^{14}C is a nuclide important for radiological dose assessments. This nuclide has a half-life of 5.7×10^3 ± 30 years and decays by beta-particle emission [20]. The ^{14}C half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 2. The results of the decay calculations using the evaluated decay codes and data libraries are presented in Table 3. In the table, the calculated ^{14}C atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{14}C using the evaluated decay codes/data libraries is illustrated in Figure 2. A relatively small dispersion of the ^{14}C atom density results is observed at long decay times (e.g. RSD ≈ 2.3% at 10^5 years), which is consistent with the differences in the ^{14}C half-life values used.

Table 2. ^{14}C half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.79878E+11	1.80821E+11	1.79874E+11	1.80821E+11	1.80800E+11
Uncertainty (s)	9.46728E+08	1.262277E+09	9.46708E+08	-	-

Sources: References 12, 13, 20 and 21.

Figure 2. Relative difference from sample mean as a function of decay time for ^{14}C atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 3. Decay calculation results for ^{14}C (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	0.00
1	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	0.00
2	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	1.845E-09	1.846E-09	1.846E-09	1.846E-09	1.846E-09	0.01
5	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	1.845E-09	0.00
10	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	1.843E-09	1.844E-09	1.844E-09	1.844E-09	1.844E-09	0.01
20	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	1.841E-09	1.842E-09	1.842E-09	1.842E-09	1.842E-09	0.01
40	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	1.837E-09	0.01
60	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	1.832E-09	1.833E-09	1.833E-09	1.833E-09	1.833E-09	0.01
80	1.829E-09	1.828E-09	1.828E-09	1.829E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	1.828E-09	0.02
100	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	1.824E-09	0.00
120	1.820E-09	1.819E-09	1.820E-09	1.820E-09	1.820E-09	1.820E-09	1.820E-09	1.820E-09	1.820E-09	1.820E-09	1.820E-09	1.819E-09	1.820E-09	1.820E-09	1.819E-09	1.820E-09	0.02
150	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	1.813E-09	0.00
200	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	1.802E-09	0.00
300	1.780E-09	1.780E-09	1.780E-09	1.781E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	1.780E-09	0.02
500	1.738E-09	1.737E-09	1.738E-09	1.738E-09	1.738E-09	1.737E-09	1.738E-09	1.738E-09	1.738E-09	1.738E-09	1.738E-09	1.737E-09	1.738E-09	1.738E-09	1.737E-09	1.738E-09	0.02
1 000	1.636E-09	1.635E-09	1.636E-09	1.636E-09	1.636E-09	1.635E-09	1.636E-09	1.636E-09	1.636E-09	1.636E-09	1.636E-09	1.635E-09	1.636E-09	1.636E-09	1.635E-09	1.636E-09	0.03
2 000	1.449E-09	1.448E-09	1.449E-09	1.450E-09	1.449E-09	1.448E-09	1.450E-09	1.450E-09	1.450E-09	1.450E-09	1.449E-09	1.449E-09	1.449E-09	1.450E-09	1.448E-09	1.449E-09	0.04
5 000	1.008E-09	1.005E-09	1.008E-09	1.008E-09	1.008E-09	1.005E-09	1.008E-09	1.008E-09	1.008E-09	1.009E-09	1.008E-09	1.008E-09	1.008E-09	1.009E-09	1.005E-09	1.008E-09	0.12
8 000	7.013E-10	6.978E-10	7.013E-10	7.014E-10	7.014E-10	6.980E-10	7.015E-10	7.015E-10	7.014E-10	7.018E-10	7.013E-10	7.011E-10	7.013E-10	7.019E-10	6.979E-10	7.007E-10	0.19
10 000	5.506E-10	5.471E-10	5.506E-10	5.507E-10	5.506E-10	5.473E-10	5.507E-10	5.507E-10	5.507E-10	5.510E-10	5.506E-10	5.504E-10	5.506E-10	5.512E-10	5.472E-10	5.500E-10	0.23
15 000	3.007E-10	2.979E-10	3.007E-10	3.007E-10	3.007E-10	2.980E-10	3.008E-10	3.008E-10	3.008E-10	3.010E-10	3.007E-10	3.006E-10	3.007E-10	3.011E-10	2.979E-10	3.002E-10	0.35
20 000	1.642E-10	1.622E-10	1.642E-10	1.642E-10	1.642E-10	1.622E-10	1.643E-10	1.643E-10	1.643E-10	1.645E-10	1.642E-10	1.641E-10	1.642E-10	1.645E-10	1.622E-10	1.639E-10	0.46
25 000	8.966E-11	8.828E-11	8.968E-11	8.970E-11	8.968E-11	8.834E-11	8.972E-11	8.972E-11	8.971E-11	8.985E-11	8.966E-11	8.964E-11	8.966E-11	8.990E-11	8.831E-11	8.943E-11	0.58
30 000	4.896E-11	4.806E-11	4.898E-11	4.899E-11	4.898E-11	4.810E-11	4.901E-11	4.901E-11	4.899E-11	4.909E-11	4.896E-11	4.895E-11	4.896E-11	4.912E-11	4.808E-11	4.881E-11	0.69
40 000	1.460E-11	1.424E-11	1.461E-11	1.461E-11	1.461E-11	1.426E-11	1.462E-11	1.462E-11	1.461E-11	1.465E-11	1.460E-11	1.460E-11	1.460E-11	1.466E-11	1.425E-11	1.454E-11	0.93
45 000	7.974E-12	7.753E-12	7.977E-12	7.979E-12	7.977E-12	7.763E-12	7.984E-12	7.984E-12	7.980E-12	8.004E-12	7.974E-12	7.972E-12	7.974E-12	8.013E-12	7.759E-12	7.938E-12	1.04
50 000	4.354E-12	4.221E-12	4.356E-12	4.358E-12	4.356E-12	4.227E-12	4.361E-12	4.361E-12	4.358E-12	4.373E-12	4.354E-12	4.353E-12	4.354E-12	4.378E-12	4.224E-12	4.333E-12	1.15
100 000	1.027E-14	9.650E-15	1.028E-14	1.029E-14	1.028E-14	9.676E-15	1.030E-14	1.030E-14	1.029E-14	1.036E-14	1.027E-14	1.027E-14	1.027E-14	1.038E-14	9.666E-15	1.017E-14	2.29

[a] ENDF/B-VI decay data. [b] JEFF-3.1 decay data.

3.2. Time-dependent ^{36}Cl atom densities

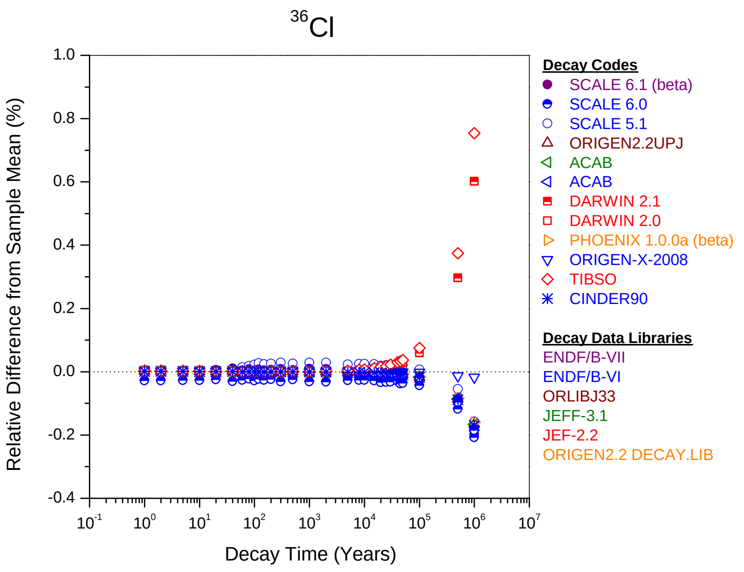
^{36}Cl is a nuclide important for radiological dose assessments. This nuclide has a half-life of $3.01 \times 10^5 \pm 2 \times 10^3$ years and decays by beta-particle emission and by electron capture [20]. The ^{36}Cl half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 4. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Tables 5 and 6. In these tables, the calculated ^{36}Cl atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{36}Cl using the evaluated decay codes/data libraries is illustrated in Figure 3. A very small dispersion of the calculated ^{36}Cl atom densities is observed at long decay times (e.g. RSD ≈ 0.4% at 10^6 years), which is consistent with the differences in the ^{36}Cl half-life values used.

Table 4. ^{36}Cl half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	9.49883E+12	9.49863E+12	9.49863E+12	9.53019E+12	9.49900E+12
Uncertainty (s)	6.31152E+10	6.31139E+10	9.46708E+10	-	-

Sources: References 12, 13, 20 and 21.

Figure 3. Relative difference from sample mean as a function of decay time for ^{36}Cl atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 5. Decay calculation results for ^{36}Cl (atom/barn·cm) *

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.00
1	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
2	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
5	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
10	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
20	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	9.999E-07	0.01
40	1.000E-06	9.999E-07	9.999E-07	1.000E-06	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.996E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	0.01
60	1.000E-06	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.996E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	0.01
80	1.000E-06	9.998E-07	9.998E-07	9.999E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.996E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	0.01
100	1.000E-06	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.995E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	0.01
120	1.000E-06	9.997E-07	9.997E-07	9.998E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.995E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	0.01
150	9.999E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.994E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	0.01
200	9.998E-07	9.995E-07	9.995E-07	9.996E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.993E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	0.01
300	9.996E-07	9.993E-07	9.993E-07	9.994E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.990E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	0.01
500	9.991E-07	9.988E-07	9.988E-07	9.989E-07	9.989E-07	9.989E-07	9.989E-07	9.989E-07	9.989E-07	9.989E-07	9.988E-07	9.986E-07	9.989E-07	9.989E-07	9.988E-07	9.989E-07	0.01
1 000	9.980E-07	9.977E-07	9.977E-07	9.978E-07	9.977E-07	9.977E-07	9.977E-07	9.977E-07	9.977E-07	9.977E-07	9.977E-07	9.974E-07	9.977E-07	9.977E-07	9.977E-07	9.977E-07	0.01
2 000	9.957E-07	9.954E-07	9.954E-07	9.955E-07	9.954E-07	9.954E-07	9.954E-07	9.954E-07	9.954E-07	9.954E-07	9.954E-07	9.951E-07	9.954E-07	9.954E-07	9.954E-07	9.954E-07	0.01
5 000	9.888E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	9.883E-07	9.886E-07	9.886E-07	9.886E-07	9.886E-07	0.01

* Table 5 continues in Table 6.

Table 6. Decay calculation results for ^{36}Cl (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
8 000	9.820E-07	9.817E-07	9.817E-07	9.818E-07	9.818E-07	9.818E-07	9.818E-07	9.818E-07	9.818E-07	9.818E-07	9.817E-07	9.815E-07	9.817E-07	9.818E-07	9.817E-07	9.818E-07	0.01
10 000	9.775E-07	9.772E-07	9.772E-07	9.773E-07	9.772E-07	9.772E-07	9.773E-07	9.773E-07	9.772E-07	9.773E-07	9.772E-07	9.770E-07	9.772E-07	9.773E-07	9.772E-07	9.773E-07	0.01
15 000	9.663E-07	9.660E-07	9.660E-07	9.661E-07	9.661E-07	9.661E-07	9.662E-07	9.662E-07	9.661E-07	9.661E-07	9.660E-07	9.658E-07	9.660E-07	9.662E-07	9.660E-07	9.661E-07	0.01
20 000	9.552E-07	9.550E-07	9.550E-07	9.550E-07	9.550E-07	9.550E-07	9.551E-07	9.551E-07	9.550E-07	9.550E-07	9.550E-07	9.547E-07	9.550E-07	9.552E-07	9.550E-07	9.550E-07	0.01
25 000	9.443E-07	9.441E-07	9.441E-07	9.441E-07	9.441E-07	9.441E-07	9.442E-07	9.442E-07	9.441E-07	9.441E-07	9.441E-07	9.438E-07	9.441E-07	9.443E-07	9.441E-07	9.441E-07	0.01
30 000	9.335E-07	9.332E-07	9.332E-07	9.333E-07	9.333E-07	9.333E-07	9.335E-07	9.335E-07	9.333E-07	9.333E-07	9.332E-07	9.330E-07	9.332E-07	9.335E-07	9.332E-07	9.333E-07	0.01
40 000	9.122E-07	9.120E-07	9.120E-07	9.121E-07	9.120E-07	9.120E-07	9.123E-07	9.123E-07	9.120E-07	9.121E-07	9.120E-07	9.118E-07	9.120E-07	9.123E-07	9.120E-07	9.121E-07	0.02
45 000	9.018E-07	9.016E-07	9.016E-07	9.016E-07	9.016E-07	9.016E-07	9.019E-07	9.019E-07	9.016E-07	9.016E-07	9.016E-07	9.013E-07	9.016E-07	9.019E-07	9.016E-07	9.016E-07	0.02
50 000	8.915E-07	8.912E-07	8.912E-07	8.913E-07	8.912E-07	8.912E-07	8.916E-07	8.916E-07	8.913E-07	8.913E-07	8.912E-07	8.910E-07	8.912E-07	8.917E-07	8.912E-07	8.913E-07	0.02
100 000	7.945E-07	7.943E-07	7.943E-07	7.943E-07	7.943E-07	7.943E-07	7.949E-07	7.949E-07	7.943E-07	7.944E-07	7.943E-07	7.941E-07	7.943E-07	7.950E-07	7.943E-07	7.944E-07	0.04
500 000	3.163E-07	3.162E-07	3.162E-07	3.162E-07	3.162E-07	3.162E-07	3.174E-07	3.174E-07	3.162E-07	3.164E-07	3.162E-07	3.161E-07	3.162E-07	3.177E-07	3.162E-07	3.165E-07	0.17
1 000 000	9.999E-08	9.995E-08	9.998E-08	9.997E-08	9.998E-08	9.998E-08	1.008E-07	1.008E-07	9.999E-08	1.001E-07	9.996E-08	9.994E-08	9.996E-08	1.009E-07	9.998E-08	1.001E-07	0.35

[a] ENDF/B-VI decay data. [b] JEFF-3.1 decay data.

3.3. Time-dependent ^{41}Ca atom densities

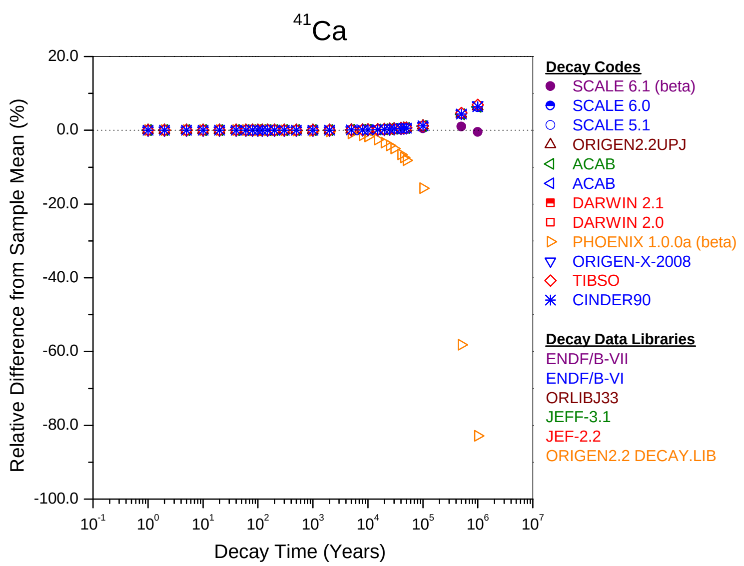
^{41}Ca is a nuclide important for radiological dose assessments. This nuclide has a half-life of $1.02\times10^5 \pm 7\times10^3$ years and decays by electron capture [20]. The ^{41}Ca half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in Table 7. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 8. In the table, the calculated ^{41}Ca atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{41}Ca using the evaluated decay codes/data libraries is illustrated in Figure 4. As seen in the figure, PHOENIX 1.0.0a (beta) predicts smaller ^{41}Ca concentrations at long decay times than the other evaluated decay codes/libraries (e.g. ~ 85% smaller at 10^6 years), which is consistent with the differences in the ^{41}Ca half-life values used.

Table 7. ^{41}Ca half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	3.21887E+12	3.25036E+12	3.25043E+12	3.25036E+12	3.25036E+12	2.55611E+12
Uncertainty (s)	2.20903E+11	1.26228E+11	1.26230E+11	-	1.26228E+11	-

Sources: References 12–14, 20 and 21.

Figure 4. Relative difference from sample mean as a function of decay time for ^{41}Ca atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 8. Decay calculation results for ^{41}Ca (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.00
1	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
2	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
5	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
10	1.000E-06	9.999E-07	9.999E-07	1.000E-06	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.997E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	0.01
20	1.000E-06	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.998E-07	9.999E-07	9.999E-07	9.996E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	0.01
40	9.999E-07	9.997E-07	9.997E-07	9.998E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	9.995E-07	9.997E-07	9.997E-07	9.997E-07	9.997E-07	0.01
60	9.997E-07	9.996E-07	9.996E-07	9.997E-07	9.996E-07	9.996E-07	9.996E-07	9.996E-07	9.995E-07	9.996E-07	9.996E-07	9.993E-07	9.996E-07	9.996E-07	9.996E-07	9.996E-07	0.01
80	9.996E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.993E-07	9.995E-07	9.995E-07	9.992E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	0.01
100	9.995E-07	9.993E-07	9.993E-07	9.994E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.992E-07	9.993E-07	9.993E-07	9.991E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	0.01
120	9.993E-07	9.992E-07	9.992E-07	9.993E-07	9.992E-07	9.992E-07	9.992E-07	9.992E-07	9.990E-07	9.992E-07	9.992E-07	9.989E-07	9.992E-07	9.992E-07	9.992E-07	9.992E-07	0.01
150	9.991E-07	9.990E-07	9.990E-07	9.991E-07	9.990E-07	9.990E-07	9.990E-07	9.990E-07	9.987E-07	9.990E-07	9.990E-07	9.987E-07	9.990E-07	9.990E-07	9.990E-07	9.990E-07	0.01
200	9.988E-07	9.986E-07	9.987E-07	9.987E-07	9.987E-07	9.987E-07	9.987E-07	9.987E-07	9.983E-07	9.987E-07	9.987E-07	9.984E-07	9.987E-07	9.987E-07	9.987E-07	9.986E-07	0.01
300	9.981E-07	9.980E-07	9.980E-07	9.980E-07	9.980E-07	9.980E-07	9.980E-07	9.980E-07	9.974E-07	9.980E-07	9.980E-07	9.977E-07	9.980E-07	9.980E-07	9.980E-07	9.979E-07	0.02
500	9.968E-07	9.966E-07	9.966E-07	9.967E-07	9.966E-07	9.966E-07	9.966E-07	9.966E-07	9.957E-07	9.966E-07	9.966E-07	9.964E-07	9.966E-07	9.966E-07	9.966E-07	9.966E-07	0.03
1 000	9.934E-07	9.932E-07	9.933E-07	9.934E-07	9.933E-07	9.933E-07	9.933E-07	9.933E-07	9.915E-07	9.933E-07	9.933E-07	9.930E-07	9.933E-07	9.933E-07	9.933E-07	9.932E-07	0.05
2 000	9.867E-07	9.865E-07	9.866E-07	9.867E-07	9.866E-07	9.866E-07	9.866E-07	9.866E-07	9.830E-07	9.866E-07	9.866E-07	9.864E-07	9.866E-07	9.866E-07	9.866E-07	9.864E-07	0.10
5 000	9.670E-07	9.666E-07	9.669E-07	9.670E-07	9.669E-07	9.669E-07	9.669E-07	9.669E-07	9.581E-07	9.669E-07	9.669E-07	9.667E-07	9.669E-07	9.669E-07	9.669E-07	9.663E-07	0.24
8 000	9.477E-07	9.471E-07	9.476E-07	9.476E-07	9.476E-07	9.476E-07	9.476E-07	9.476E-07	9.338E-07	9.476E-07	9.476E-07	9.473E-07	9.476E-07	9.476E-07	9.476E-07	9.466E-07	0.39
10 000	9.350E-07	9.343E-07	9.349E-07	9.350E-07	9.349E-07	9.349E-07	9.349E-07	9.349E-07	9.180E-07	9.350E-07	9.349E-07	9.347E-07	9.349E-07	9.350E-07	9.349E-07	9.337E-07	0.48
15 000	9.041E-07	9.031E-07	9.040E-07	9.040E-07	9.040E-07	9.040E-07	9.040E-07	9.040E-07	8.796E-07	9.040E-07	9.040E-07	9.037E-07	9.040E-07	9.040E-07	9.040E-07	9.023E-07	0.72
20 000	8.742E-07	8.729E-07	8.741E-07	8.741E-07	8.741E-07	8.741E-07	8.741E-07	8.741E-07	8.427E-07	8.742E-07	8.740E-07	8.738E-07	8.740E-07	8.742E-07	8.741E-07	8.719E-07	0.96
25 000	8.452E-07	8.437E-07	8.452E-07	8.452E-07	8.451E-07	8.451E-07	8.452E-07	8.452E-07	8.074E-07	8.452E-07	8.451E-07	8.449E-07	8.451E-07	8.452E-07	8.452E-07	8.425E-07	1.19
30 000	8.173E-07	8.156E-07	8.172E-07	8.172E-07	8.172E-07	8.172E-07	8.172E-07	8.172E-07	7.736E-07	8.173E-07	8.172E-07	8.169E-07	8.172E-07	8.173E-07	8.172E-07	8.142E-07	1.43
40 000	7.641E-07	7.620E-07	7.640E-07	7.640E-07	7.640E-07	7.640E-07	7.640E-07	7.640E-07	7.102E-07	7.641E-07	7.640E-07	7.638E-07	7.640E-07	7.641E-07	7.640E-07	7.603E-07	1.89
45 000	7.388E-07	7.365E-07	7.387E-07	7.387E-07	7.387E-07	7.387E-07	7.387E-07	7.387E-07	6.804E-07	7.389E-07	7.387E-07	7.385E-07	7.387E-07	7.389E-07	7.387E-07	7.347E-07	2.12
50 000	7.143E-07	7.119E-07	7.143E-07	7.143E-07	7.143E-07	7.143E-07	7.143E-07	7.143E-07	6.519E-07	7.144E-07	7.142E-07	7.140E-07	7.142E-07	7.144E-07	7.143E-07	7.100E-07	2.34
100 000	5.102E-07	5.068E-07	5.102E-07	5.102E-07	5.102E-07	5.102E-07	5.102E-07	5.102E-07	4.250E-07	5.104E-07	5.101E-07	5.100E-07	5.101E-07	5.104E-07	5.102E-07	5.043E-07	4.51
500 000	3.455E-08	3.344E-08	3.457E-08	3.455E-08	3.455E-08	3.455E-08	3.457E-08	3.457E-08	1.386E-08	3.465E-08	3.454E-08	3.454E-08	3.454E-08	3.465E-08	3.457E-08	3.311E-08	16.67
1 000 000	1.193E-09	1.118E-09	1.195E-09	1.193E-09	1.194E-09	1.194E-09	1.195E-09	1.195E-09	1.921E-10	1.200E-09	1.193E-09	1.193E-09	1.193E-09	1.201E-09	1.195E-09	1.123E-09	23.80

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.4. Time-dependent ^{59}Ni atom densities

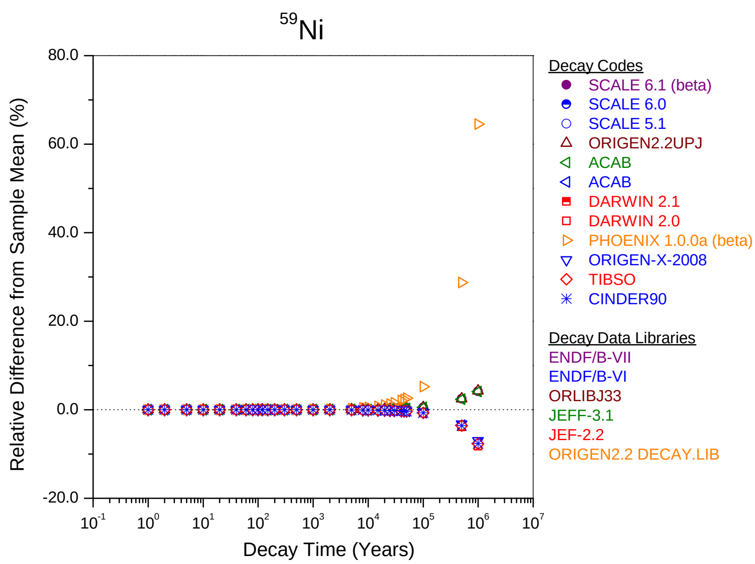
^{59}Ni is a nuclide important for radiological dose assessments. This nuclide has a half-life of 7.6×10^4 ± 5×10^3 years and decays by electron capture and positron emission [20]. The ^{59}Ni half-life values and the uncertainties associated with the half-life values in ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 9. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 10. In the table, the calculated ^{59}Ni atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{59}Ni using the evaluated decay codes/data libraries is illustrated in Figure 5. As seen in the figure, PHOENIX 1.0.0a (beta) predicts higher ^{59}Ni concentrations at long decay times than the other evaluated decay codes/libraries (e.g. ~ 70% higher at 10^6 years), which is consistent with the differences in the ^{59}Ni half-life values used.

Table 9. ^{59}Ni half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.39837E+12	2.36677E+12	2.39838E+12	2.36361E+12	2.39837E+12	2.52455E+12
Uncertainty (s)	1.57788E+11	4.10240E+11	1.57788E+11	-	1.57788E+11	-

Sources: References 12–14, 20 and 21.

Figure 5. Relative difference from sample mean as a function of decay time for ^{59}Ni atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 10. Decay calculation results for ^{59}Ni (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.00
1	9.999E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
2	9.999E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	0.01
5	9.999E-07	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	1.000E-06	9.997E-07	1.000E-06	1.000E-06	1.000E-06	9.999E-07	0.01
10	9.998E-07	9.999E-07	9.999E-07	1.000E-06	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	9.996E-07	9.999E-07	9.999E-07	9.999E-07	9.999E-07	0.01
20	9.997E-07	9.998E-07	9.998E-07	9.999E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	9.996E-07	9.998E-07	9.998E-07	9.998E-07	9.998E-07	0.01
40	9.995E-07	9.996E-07	9.996E-07	9.997E-07	9.996E-07	9.996E-07	9.996E-07	9.996E-07	9.997E-07	9.996E-07	9.996E-07	9.994E-07	9.996E-07	9.996E-07	9.996E-07	9.996E-07	0.01
60	9.994E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.995E-07	9.992E-07	9.994E-07	9.994E-07	9.994E-07	9.994E-07	0.01
80	9.992E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.993E-07	9.990E-07	9.993E-07	9.993E-07	9.993E-07	9.992E-07	0.01
100	9.990E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	9.988E-07	9.991E-07	9.991E-07	9.991E-07	9.991E-07	0.01
120	9.988E-07	9.989E-07	9.989E-07	9.990E-07	9.989E-07	9.989E-07	9.989E-07	9.989E-07	9.990E-07	9.989E-07	9.989E-07	9.986E-07	9.989E-07	9.989E-07	9.989E-07	9.989E-07	0.01
150	9.985E-07	9.986E-07	9.986E-07	9.987E-07	9.986E-07	9.986E-07	9.986E-07	9.986E-07	9.987E-07	9.986E-07	9.986E-07	9.984E-07	9.986E-07	9.986E-07	9.986E-07	9.986E-07	0.01
200	9.981E-07	9.982E-07	9.982E-07	9.982E-07	9.982E-07	9.982E-07	9.982E-07	9.982E-07	9.983E-07	9.982E-07	9.982E-07	9.979E-07	9.982E-07	9.982E-07	9.982E-07	9.981E-07	0.01
300	9.971E-07	9.973E-07	9.973E-07	9.973E-07	9.972E-07	9.973E-07	9.972E-07	9.972E-07	9.974E-07	9.972E-07	9.972E-07	9.970E-07	9.972E-07	9.972E-07	9.972E-07	9.972E-07	0.01
500	9.953E-07	9.954E-07	9.955E-07	9.955E-07	9.954E-07	9.955E-07	9.954E-07	9.954E-07	9.957E-07	9.954E-07	9.954E-07	9.951E-07	9.954E-07	9.954E-07	9.954E-07	9.954E-07	0.01
1 000	9.907E-07	9.909E-07	9.909E-07	9.909E-07	9.908E-07	9.909E-07	9.908E-07	9.908E-07	9.914E-07	9.908E-07	9.908E-07	9.905E-07	9.908E-07	9.908E-07	9.908E-07	9.908E-07	0.02
2 000	9.816E-07	9.819E-07	9.819E-07	9.817E-07	9.817E-07	9.819E-07	9.817E-07	9.817E-07	9.828E-07	9.817E-07	9.817E-07	9.814E-07	9.817E-07	9.817E-07	9.817E-07	9.818E-07	0.03
5 000	9.548E-07	9.554E-07	9.554E-07	9.549E-07	9.548E-07	9.554E-07	9.548E-07	9.548E-07	9.576E-07	9.549E-07	9.548E-07	9.546E-07	9.548E-07	9.548E-07	9.548E-07	9.551E-07	0.08
8 000	9.286E-07	9.296E-07	9.296E-07	9.288E-07	9.287E-07	9.296E-07	9.287E-07	9.287E-07	9.330E-07	9.288E-07	9.287E-07	9.285E-07	9.287E-07	9.287E-07	9.287E-07	9.292E-07	0.13
10 000	9.116E-07	9.128E-07	9.128E-07	9.118E-07	9.117E-07	9.128E-07	9.117E-07	9.117E-07	9.170E-07	9.118E-07	9.117E-07	9.115E-07	9.117E-07	9.117E-07	9.117E-07	9.123E-07	0.16
15 000	8.705E-07	8.721E-07	8.721E-07	8.706E-07	8.706E-07	8.721E-07	8.705E-07	8.705E-07	8.781E-07	8.707E-07	8.706E-07	8.703E-07	8.705E-07	8.706E-07	8.706E-07	8.714E-07	0.24
20 000	8.312E-07	8.332E-07	8.333E-07	8.313E-07	8.313E-07	8.332E-07	8.311E-07	8.311E-07	8.409E-07	8.314E-07	8.312E-07	8.310E-07	8.312E-07	8.312E-07	8.312E-07	8.323E-07	0.32
25 000	7.936E-07	7.961E-07	7.961E-07	7.938E-07	7.937E-07	7.961E-07	7.936E-07	7.936E-07	8.053E-07	7.939E-07	7.937E-07	7.935E-07	7.937E-07	7.937E-07	7.937E-07	7.950E-07	0.41
30 000	7.578E-07	7.606E-07	7.606E-07	7.579E-07	7.579E-07	7.606E-07	7.577E-07	7.577E-07	7.711E-07	7.580E-07	7.579E-07	7.577E-07	7.579E-07	7.579E-07	7.579E-07	7.594E-07	0.49
40 000	6.909E-07	6.943E-07	6.943E-07	6.910E-07	6.910E-07	6.943E-07	6.908E-07	6.908E-07	7.071E-07	6.912E-07	6.910E-07	6.908E-07	6.910E-07	6.910E-07	6.910E-07	6.928E-07	0.65
45 000	6.597E-07	6.633E-07	6.634E-07	6.598E-07	6.598E-07	6.633E-07	6.596E-07	6.596E-07	6.771E-07	6.600E-07	6.598E-07	6.596E-07	6.598E-07	6.598E-07	6.598E-07	6.617E-07	0.73
50 000	6.299E-07	6.338E-07	6.338E-07	6.300E-07	6.300E-07	6.338E-07	6.298E-07	6.298E-07	6.484E-07	6.302E-07	6.300E-07	6.298E-07	6.300E-07	6.300E-07	6.300E-07	6.321E-07	0.81
100 000	3.968E-07	4.017E-07	4.017E-07	3.969E-07	3.969E-07	4.017E-07	3.966E-07	3.966E-07	4.205E-07	3.971E-07	3.969E-07	3.967E-07	3.968E-07	3.968E-07	3.969E-07	3.996E-07	1.64
500 000	9.842E-09	1.046E-08	1.046E-08	9.844E-09	9.847E-09	1.045E-08	9.813E-09	9.813E-09	1.314E-08	9.879E-09	9.843E-09	9.840E-09	9.843E-09	9.844E-09	9.844E-09	1.021E-08	8.94
1 000 000	9.687E-11	1.093E-10	1.094E-10	9.689E-11	9.696E-11	1.093E-10	9.629E-11	9.629E-11	1.726E-10	9.760E-11	9.688E-11	9.686E-11	9.688E-11	9.690E-11	9.690E-11	1.049E-10	19.89

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.5. Time-dependent ^{79}Se atom densities

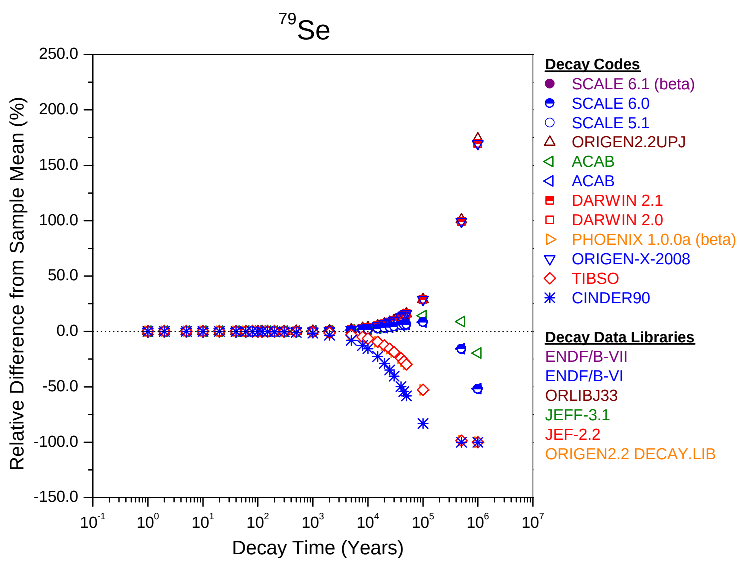
^{79}Se is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of 2.95×10^5 ± 3.8×10^4 years and decays by beta-particle emission [20]. The ^{79}Se half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 11. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 12. In the table, the calculated ^{79}Se atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{79}Se using the evaluated decay codes/data libraries is illustrated in Figure 6. As seen in the figure, there is a very significant dispersion of the calculated ^{79}Se atom density values at long decay times (e.g. RSD ≈ 110% at 10^6 years), which is consistent with the significant variability in the ^{79}Se half-life values utilised by the evaluated decay codes/libraries. The uncertainties associated with the ENDF/B-VII.0 and JEFF-3.1 half-life values for ^{79}Se are approximately 13% and 5%, respectively.

Table 11. ^{79}Se half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	9.30949E+12	1.04138E+12	1.18970E+13	2.05120E+12	2.05124E+12	2.05000E+12
Uncertainty (s)	1.19918E+12	1.00982E+12	5.99582E+11	-	-	-

Sources: References 12–14, 20 and 21.

Figure 6. Relative difference from sample mean as a function of decay time for ^{79}Se atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 12. Decay calculation results for ^{79}Se (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	0.00
1	5.058E-07	5.058E-07	5.058E-07	5.059E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	0.01
2	5.058E-07	5.058E-07	5.058E-07	5.059E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	0.01
5	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	0.01
10	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	0.01
20	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.057E-07	5.056E-07	5.058E-07	0.01
40	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.056E-07	5.058E-07	5.058E-07	5.056E-07	5.058E-07	5.056E-07	5.054E-07	5.057E-07	0.02
60	5.057E-07	5.057E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.058E-07	5.055E-07	5.058E-07	5.057E-07	5.056E-07	5.057E-07	5.055E-07	5.052E-07	5.057E-07	0.02
80	5.057E-07	5.057E-07	5.058E-07	5.058E-07	5.057E-07	5.058E-07	5.058E-07	5.058E-07	5.054E-07	5.058E-07	5.057E-07	5.056E-07	5.057E-07	5.054E-07	5.050E-07	5.056E-07	0.03
100	5.057E-07	5.057E-07	5.058E-07	5.057E-07	5.057E-07	5.057E-07	5.058E-07	5.058E-07	5.053E-07	5.058E-07	5.057E-07	5.056E-07	5.057E-07	5.053E-07	5.048E-07	5.056E-07	0.03
120	5.057E-07	5.057E-07	5.058E-07	5.057E-07	5.057E-07	5.057E-07	5.058E-07	5.058E-07	5.052E-07	5.058E-07	5.057E-07	5.055E-07	5.057E-07	5.052E-07	5.045E-07	5.056E-07	0.04
150	5.056E-07	5.056E-07	5.058E-07	5.057E-07	5.056E-07	5.057E-07	5.058E-07	5.058E-07	5.050E-07	5.058E-07	5.056E-07	5.055E-07	5.056E-07	5.050E-07	5.042E-07	5.055E-07	0.05
200	5.056E-07	5.056E-07	5.058E-07	5.056E-07	5.056E-07	5.056E-07	5.058E-07	5.058E-07	5.047E-07	5.058E-07	5.056E-07	5.054E-07	5.056E-07	5.047E-07	5.037E-07	5.054E-07	0.07
300	5.054E-07	5.055E-07	5.057E-07	5.055E-07	5.055E-07	5.055E-07	5.057E-07	5.057E-07	5.042E-07	5.057E-07	5.055E-07	5.053E-07	5.055E-07	5.042E-07	5.026E-07	5.052E-07	0.10
500	5.052E-07	5.052E-07	5.057E-07	5.053E-07	5.052E-07	5.054E-07	5.057E-07	5.057E-07	5.031E-07	5.057E-07	5.052E-07	5.051E-07	5.052E-07	5.031E-07	5.005E-07	5.048E-07	0.17
1 000	5.046E-07	5.046E-07	5.055E-07	5.047E-07	5.046E-07	5.049E-07	5.055E-07	5.055E-07	5.005E-07	5.055E-07	5.046E-07	5.045E-07	5.046E-07	5.005E-07	4.953E-07	5.037E-07	0.33
2 000	5.034E-07	5.034E-07	5.052E-07	5.035E-07	5.035E-07	5.040E-07	5.052E-07	5.052E-07	4.951E-07	5.052E-07	5.034E-07	5.033E-07	5.034E-07	4.952E-07	4.850E-07	5.016E-07	0.66
5 000	4.999E-07	4.999E-07	5.043E-07	4.999E-07	4.999E-07	5.012E-07	5.042E-07	5.042E-07	4.796E-07	5.042E-07	4.999E-07	4.998E-07	4.999E-07	4.796E-07	4.554E-07	4.955E-07	1.65
8 000	4.964E-07	4.964E-07	5.033E-07	4.964E-07	4.964E-07	4.984E-07	5.033E-07	5.033E-07	4.644E-07	5.033E-07	4.964E-07	4.963E-07	4.964E-07	4.645E-07	4.276E-07	4.895E-07	2.63
10 000	4.940E-07	4.941E-07	5.027E-07	4.941E-07	4.941E-07	4.966E-07	5.026E-07	5.026E-07	4.546E-07	5.027E-07	4.941E-07	4.939E-07	4.941E-07	4.547E-07	4.100E-07	4.857E-07	3.27
15 000	4.883E-07	4.883E-07	5.012E-07	4.883E-07	4.883E-07	4.921E-07	5.011E-07	5.011E-07	4.310E-07	5.011E-07	4.883E-07	4.882E-07	4.883E-07	4.311E-07	3.691E-07	4.764E-07	4.86
20 000	4.826E-07	4.826E-07	4.997E-07	4.826E-07	4.826E-07	4.876E-07	4.995E-07	4.995E-07	4.086E-07	4.995E-07	4.826E-07	4.824E-07	4.826E-07	4.087E-07	3.323E-07	4.676E-07	6.41
25 000	4.769E-07	4.770E-07	4.981E-07	4.770E-07	4.769E-07	4.831E-07	4.979E-07	4.979E-07	3.874E-07	4.979E-07	4.769E-07	4.768E-07	4.769E-07	3.875E-07	2.992E-07	4.592E-07	7.93
30 000	4.713E-07	4.714E-07	4.966E-07	4.714E-07	4.714E-07	4.787E-07	4.964E-07	4.964E-07	3.673E-07	4.964E-07	4.714E-07	4.712E-07	4.714E-07	3.674E-07	2.694E-07	4.512E-07	9.42
40 000	4.604E-07	4.604E-07	4.936E-07	4.604E-07	4.604E-07	4.700E-07	4.932E-07	4.932E-07	3.301E-07	4.932E-07	4.604E-07	4.603E-07	4.604E-07	3.303E-07	2.183E-07	4.363E-07	12.28
45 000	4.550E-07	4.551E-07	4.920E-07	4.550E-07	4.550E-07	4.657E-07	4.917E-07	4.917E-07	3.130E-07	4.917E-07	4.550E-07	4.549E-07	4.550E-07	3.131E-07	1.966E-07	4.294E-07	13.66
50 000	4.497E-07	4.497E-07	4.905E-07	4.497E-07	4.497E-07	4.614E-07	4.901E-07	4.901E-07	2.967E-07	4.901E-07	4.497E-07	4.496E-07	4.497E-07	2.969E-07	1.770E-07	4.227E-07	14.99
100 000	3.998E-07	3.999E-07	4.757E-07	3.998E-07	3.998E-07	4.209E-07	4.749E-07	4.749E-07	1.740E-07	4.750E-07	3.998E-07	3.997E-07	3.998E-07	1.743E-07	6.192E-08	3.687E-07	26.47
500 000	1.560E-07	1.562E-07	3.722E-07	1.560E-07	1.561E-07	2.018E-07	3.691E-07	3.691E-07	2.438E-09	3.692E-07	1.560E-07	1.560E-07	1.560E-07	2.455E-09	1.390E-11	1.852E-07	68.13
1 000 000	4.813E-08	4.825E-08	2.739E-07	4.813E-08	4.814E-08	8.048E-08	2.694E-07	2.694E-07	1.175E-11	2.695E-07	4.813E-08	4.812E-08	4.813E-08	1.191E-11	6.193E-16	9.998E-08	109.15

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.6. Time-dependent ^{90}Sr atom densities

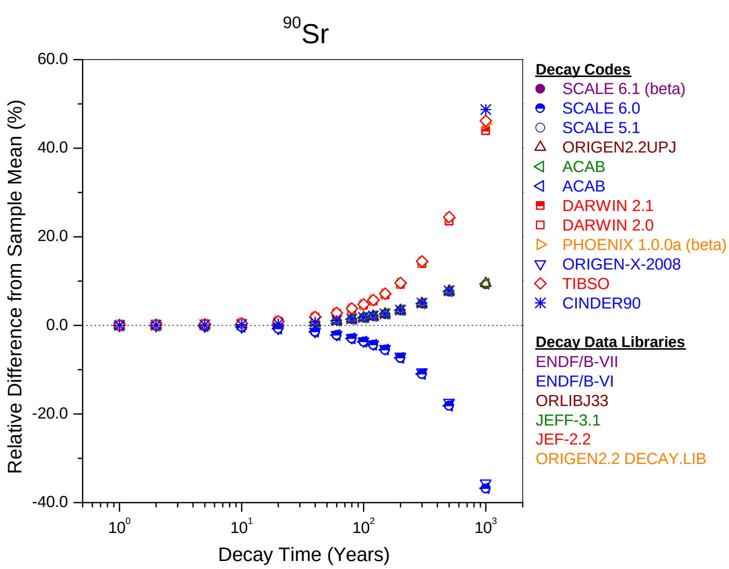
^{90}Sr is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of 28.79 ± 0.6 years and decays by beta-particle emission [20]. The ^{90}Sr half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 13. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 14. In the table, the calculated ^{90}Sr atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{90}Sr using the evaluated decay codes/data libraries is illustrated in Figure 7. As seen in the figure, there is a significant dispersion of the calculated ^{90}Sr atom density values at long decay times (e.g. RSD ≈ 37% at 10^3 years), which is consistent with the variability in the ^{90}Sr half-life values utilised by the evaluated decay codes/libraries.

Table 13. ^{90}Sr half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	9.08543E+08	8.88327E+08	9.08524E+08	9.18938E+08	9.08226E+08	9.19000E+08
Uncertainty (s)	1.89346E+06	3.15569E+06	1.89342E+06	-	1.26228E+06	-

Sources: References 12–14, 20 and 21.

Figure 7. Relative difference from sample mean as a function of decay time for ^{90}Sr atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 14. Decay calculation results for ^{90}Sr (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	4.858E-05	0.00
1	4.740E-05	4.743E-05	4.743E-05	4.741E-05	4.740E-05	4.743E-05	4.744E-05	4.744E-05	4.744E-05	4.740E-05	4.740E-05	4.739E-05	4.740E-05	4.744E-05	4.743E-05	4.742E-05	0.04
2	4.625E-05	4.630E-05	4.630E-05	4.625E-05	4.625E-05	4.630E-05	4.633E-05	4.633E-05	4.633E-05	4.625E-05	4.625E-05	4.624E-05	4.625E-05	4.633E-05	4.630E-05	4.628E-05	0.08
5	4.295E-05	4.307E-05	4.307E-05	4.296E-05	4.296E-05	4.307E-05	4.313E-05	4.313E-05	4.313E-05	4.296E-05	4.296E-05	4.294E-05	4.296E-05	4.314E-05	4.307E-05	4.303E-05	0.19
10	3.798E-05	3.819E-05	3.819E-05	3.798E-05	3.798E-05	3.819E-05	3.829E-05	3.829E-05	3.830E-05	3.799E-05	3.798E-05	3.797E-05	3.798E-05	3.830E-05	3.819E-05	3.812E-05	0.38
20	2.969E-05	3.002E-05	3.002E-05	2.969E-05	2.969E-05	3.002E-05	3.018E-05	3.018E-05	3.019E-05	2.970E-05	2.969E-05	2.968E-05	2.969E-05	3.019E-05	3.002E-05	2.991E-05	0.76
40	1.814E-05	1.854E-05	1.855E-05	1.814E-05	1.814E-05	1.855E-05	1.875E-05	1.875E-05	1.876E-05	1.816E-05	1.814E-05	1.814E-05	1.814E-05	1.876E-05	1.855E-05	1.841E-05	1.53
60	1.109E-05	1.146E-05	1.146E-05	1.109E-05	1.109E-05	1.146E-05	1.165E-05	1.165E-05	1.166E-05	1.110E-05	1.109E-05	1.108E-05	1.109E-05	1.166E-05	1.146E-05	1.134E-05	2.29
80	6.775E-06	7.078E-06	7.080E-06	6.775E-06	6.776E-06	7.079E-06	7.236E-06	7.236E-06	7.242E-06	6.785E-06	6.775E-06	6.773E-06	6.775E-06	7.245E-06	7.080E-06	6.981E-06	3.05
100	4.140E-06	4.373E-06	4.374E-06	4.140E-06	4.141E-06	4.374E-06	4.495E-06	4.495E-06	4.500E-06	4.148E-06	4.140E-06	4.139E-06	4.140E-06	4.502E-06	4.375E-06	4.298E-06	3.82
120	2.530E-06	2.702E-06	2.703E-06	2.530E-06	2.530E-06	2.702E-06	2.793E-06	2.793E-06	2.796E-06	2.536E-06	2.530E-06	2.529E-06	2.530E-06	2.798E-06	2.703E-06	2.647E-06	4.58
150	1.209E-06	1.312E-06	1.312E-06	1.209E-06	1.209E-06	1.312E-06	1.367E-06	1.367E-06	1.370E-06	1.212E-06	1.209E-06	1.208E-06	1.209E-06	1.371E-06	1.313E-06	1.279E-06	5.72
200	3.528E-07	3.936E-07	3.938E-07	3.528E-07	3.529E-07	3.937E-07	4.159E-07	4.159E-07	4.168E-07	3.541E-07	3.528E-07	3.527E-07	3.528E-07	4.172E-07	3.939E-07	3.808E-07	7.64
300	3.006E-08	3.543E-08	3.545E-08	3.007E-08	3.007E-08	3.544E-08	3.848E-08	3.848E-08	3.861E-08	3.023E-08	3.006E-08	3.006E-08	3.006E-08	3.867E-08	3.547E-08	3.378E-08	11.46
500	2.183E-10	2.870E-10	2.874E-10	2.183E-10	2.184E-10	2.872E-10	3.295E-10	3.295E-10	3.312E-10	2.204E-10	2.183E-10	2.183E-10	2.183E-10	3.321E-10	2.875E-10	2.668E-10	19.10
1 000	9.809E-16	1.696E-15	1.700E-15	9.810E-16	9.821E-16	1.698E-15	2.234E-15	2.234E-15	2.258E-15	9.995E-16	9.810E-16	9.807E-16	9.810E-16	2.270E-15	2.309E-15	1.552E-15	36.74

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.7. Time-dependent ^{93}Zr atom densities

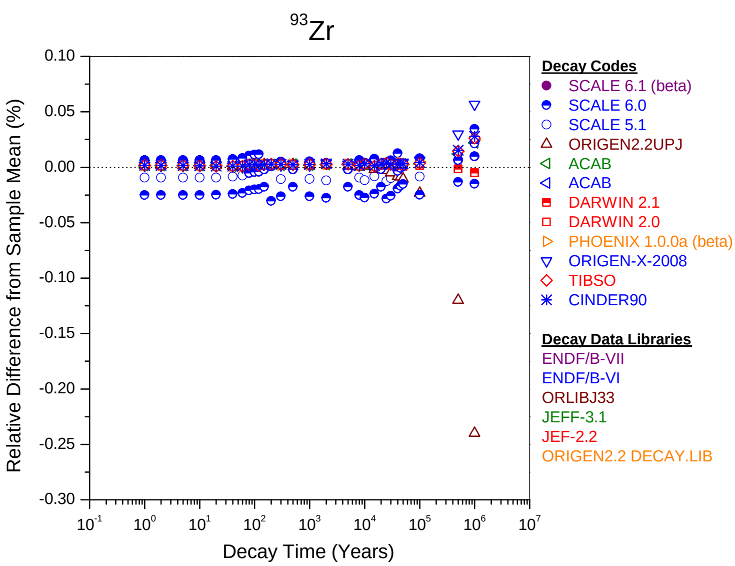
^{93}Zr is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of $1.53\times10^6 \pm 1.0\times10^5$ years and decays by beta-particle emission [20]. The ^{93}Zr half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 15. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 16. In the table, the calculated ^{93}Zr atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{93}Zr using the evaluated decay codes/data libraries is illustrated in Figure 8. The dispersion of the ^{93}Zr results is insignificant at long decay times.

Table 15. ^{93}Zr half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	4.82831E+13	4.82821E+13	4.82821E+13	4.82821E+13	4.80000E+13	4.82800E+13
Uncertainty (s)	3.15576E+12	3.15569E+12	3.15569E+12	-	4.00000E+12	-

Sources: References 12, 13, 15, 20 and 21.

Figure 8. Relative difference from sample mean as a function of decay time for ^{93}Zr atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 16. Decay calculation results for ^{93}Zr (atom/barn·cm)

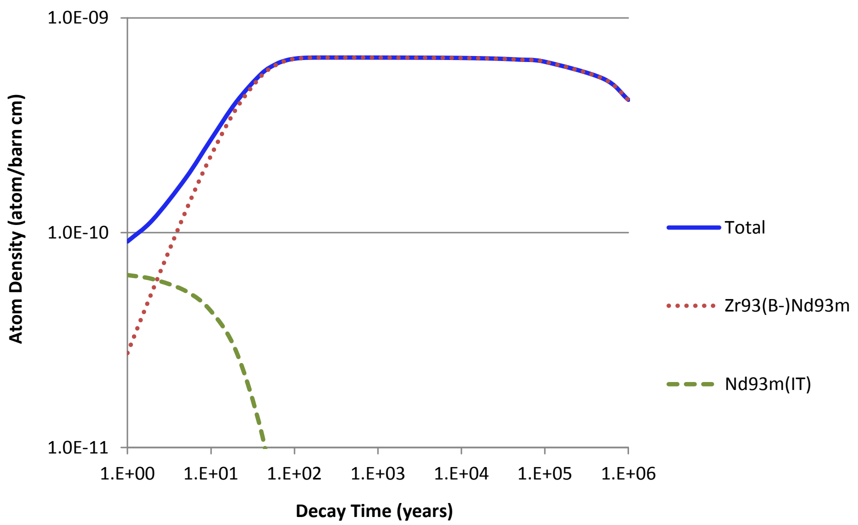
Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	0.00
1	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	0.01
2	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	0.01
5	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	0.01
10	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	0.01
20	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	0.01
40	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	0.01
60	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.364E-05	6.366E-05	6.366E-05	6.366E-05	6.365E-05	0.01
80	6.365E-05	6.366E-05	6.365E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.366E-05	6.365E-05	6.364E-05	6.366E-05	6.365E-05	6.365E-05	6.365E-05	0.01
100	6.365E-05	6.365E-05	6.365E-05	6.366E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.364E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	0.01
120	6.365E-05	6.365E-05	6.365E-05	6.366E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.364E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	0.01
150	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.364E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	0.01
200	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.363E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	0.01
300	6.364E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	6.363E-05	6.365E-05	6.365E-05	6.365E-05	6.365E-05	0.01
500	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	6.363E-05	6.364E-05	6.364E-05	6.364E-05	6.364E-05	0.01
1 000	6.362E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	6.361E-05	6.363E-05	6.363E-05	6.363E-05	6.363E-05	0.01
2 000	6.359E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	6.358E-05	6.360E-05	6.360E-05	6.360E-05	6.360E-05	0.01
5 000	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	6.350E-05	6.351E-05	6.351E-05	6.351E-05	6.351E-05	0.01
8 000	6.342E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	6.341E-05	6.343E-05	6.343E-05	6.343E-05	6.343E-05	0.01
10 000	6.336E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	6.335E-05	6.337E-05	6.337E-05	6.337E-05	6.337E-05	0.01
15 000	6.322E-05	6.323E-05	6.322E-05	6.323E-05	6.323E-05	6.323E-05	6.323E-05	6.323E-05	6.323E-05	6.323E-05	6.323E-05	6.321E-05	6.323E-05	6.323E-05	6.323E-05	6.322E-05	0.01
20 000	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	6.307E-05	6.308E-05	6.308E-05	6.308E-05	6.308E-05	0.01
25 000	6.293E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	6.292E-05	6.294E-05	6.294E-05	6.294E-05	6.294E-05	0.01
30 000	6.279E-05	6.280E-05	6.279E-05	6.280E-05	6.280E-05	6.280E-05	6.280E-05	6.280E-05	6.280E-05	6.280E-05	6.280E-05	6.278E-05	6.280E-05	6.280E-05	6.280E-05	6.280E-05	0.01
40 000	6.251E-05	6.251E-05	6.251E-05	6.252E-05	6.251E-05	6.251E-05	6.251E-05	6.251E-05	6.251E-05	6.252E-05	6.251E-05	6.250E-05	6.251E-05	6.251E-05	6.251E-05	6.251E-05	0.01
45 000	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	6.236E-05	6.237E-05	6.237E-05	6.237E-05	6.237E-05	0.01
50 000	6.223E-05	6.223E-05	6.222E-05	6.223E-05	6.223E-05	6.223E-05	6.223E-05	6.223E-05	6.223E-05	6.223E-05	6.223E-05	6.222E-05	6.223E-05	6.223E-05	6.223E-05	6.223E-05	0.01
100 000	6.083E-05	6.084E-05	6.082E-05	6.084E-05	6.084E-05	6.084E-05	6.084E-05	6.084E-05	6.084E-05	6.084E-05	6.084E-05	6.082E-05	6.084E-05	6.084E-05	6.084E-05	6.083E-05	0.01
500 000	5.075E-05	5.075E-05	5.069E-05	5.075E-05	5.075E-05	5.075E-05	5.075E-05	5.075E-05	5.075E-05	5.076E-05	5.075E-05	5.074E-05	5.075E-05	5.075E-05	5.075E-05	5.075E-05	0.04
1 000 000	4.046E-05	4.046E-05	4.036E-05	4.047E-05	4.047E-05	4.047E-05	4.045E-05	4.045E-05	4.047E-05	4.048E-05	4.046E-05	4.045E-05	4.046E-05	4.047E-05	4.047E-05	4.046E-05	0.07

[a] ENDF/B-VI decay data.
[b] JEFF-3.1 decay data.

3.8. Time-dependent ^{93m}Nb atom densities

^{93m}Nb is a metastable isomer important for radiological dose assessments. This nuclide has a half-life of 16.13 ± 0.14 years and decays by isomeric transition [20]. The beta transition of ^{93}Zr ($T_{1/2}$ = $1.53\times10^6 \pm 1.0\times10^5$ years) to ^{93m}Nb is the major production path for long-term ^{93m}Nb concentrations. The cumulative ^{93m}Nb atom density is illustrated as a function of decay time in Figure 9.

Figure 9. ^{93m}Nb atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; B- denotes beta decay; IT denotes isomeric transition.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 17. In the table, the calculated ^{93m}Nb atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{93m}Nb using the evaluated decay codes/data libraries is illustrated in Figure 10. The ^{93m}Nb half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 18. The values of the ^{93}Zr branching ratio for beta decay in the ENDF/B-VII.0, ENDF/B-VI, JEFF-3.1, JEF-2.2, JENDL FP, and ORIGEN2.2 DECAY.LIB libraries are 0.975, 1.0, 0.975, 1.0, 0.95, and 0.95, respectively. A recently published value for the branching ratio is 0.73 ± 0.05 [22]. The dispersion of the results observed at long decay time may be attributed to the different values for ^{93}Zr half-life (see Table 15) and branching ratio for beta decay associated with the evaluated codes/libraries.

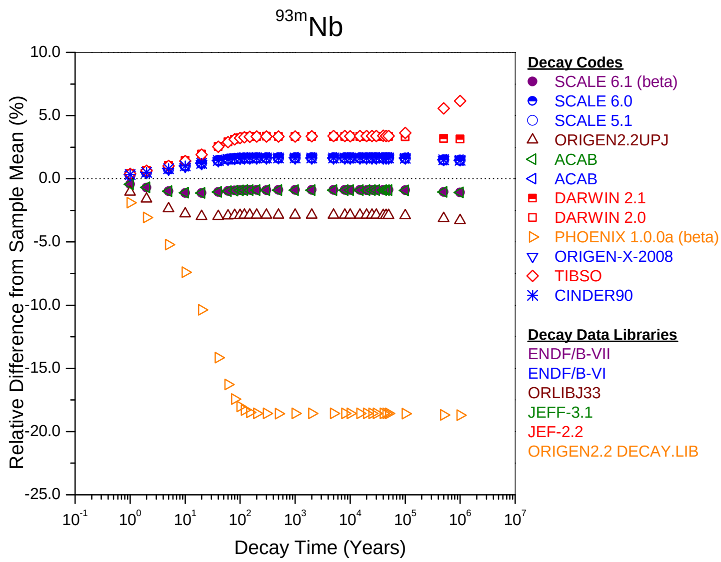
Table 17. Decay calculation results for ^{93m}Nb (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	6.631E-11	0.00
1	9.172E-11	9.104E-11	9.049E-11	9.175E-11	9.175E-11	9.104E-11	9.182E-11	9.182E-11	8.971E-11	9.173E-11	9.175E-11	9.172E-11	9.175E-11	9.180E-11	9.174E-11	9.144E-11	0.69
2	1.161E-10	1.147E-10	1.137E-10	1.161E-10	1.161E-10	1.147E-10	1.163E-10	1.163E-10	1.120E-10	1.161E-10	1.161E-10	1.161E-10	1.161E-10	1.162E-10	1.161E-10	1.155E-10	1.11
5	1.832E-10	1.800E-10	1.775E-10	1.833E-10	1.833E-10	1.800E-10	1.837E-10	1.837E-10	1.723E-10	1.832E-10	1.833E-10	1.832E-10	1.833E-10	1.837E-10	1.832E-10	1.818E-10	1.81
10	2.776E-10	2.717E-10	2.672E-10	2.776E-10	2.776E-10	2.717E-10	2.788E-10	2.788E-10	2.545E-10	2.775E-10	2.776E-10	2.775E-10	2.776E-10	2.786E-10	2.776E-10	2.748E-10	2.45
20	4.150E-10	4.054E-10	3.978E-10	4.151E-10	4.151E-10	4.053E-10	4.179E-10	4.179E-10	3.675E-10	4.149E-10	4.151E-10	4.149E-10	4.151E-10	4.178E-10	4.150E-10	4.100E-10	3.29
40	5.626E-10	5.489E-10	5.382E-10	5.627E-10	5.627E-10	5.489E-10	5.689E-10	5.689E-10	4.762E-10	5.626E-10	5.627E-10	5.626E-10	5.627E-10	5.687E-10	5.627E-10	5.547E-10	4.34
60	6.251E-10	6.097E-10	5.976E-10	6.252E-10	6.252E-10	6.096E-10	6.336E-10	6.336E-10	5.154E-10	6.251E-10	6.252E-10	6.250E-10	6.252E-10	6.335E-10	6.252E-10	6.156E-10	4.94
80	6.516E-10	6.354E-10	6.228E-10	6.517E-10	6.517E-10	6.353E-10	6.614E-10	6.614E-10	5.296E-10	6.516E-10	6.517E-10	6.515E-10	6.517E-10	6.613E-10	6.516E-10	6.414E-10	5.27
100	6.628E-10	6.463E-10	6.334E-10	6.629E-10	6.629E-10	6.462E-10	6.733E-10	6.733E-10	5.347E-10	6.628E-10	6.629E-10	6.627E-10	6.629E-10	6.733E-10	6.628E-10	6.522E-10	5.44
120	6.675E-10	6.509E-10	6.379E-10	6.676E-10	6.676E-10	6.508E-10	6.785E-10	6.785E-10	5.365E-10	6.676E-10	6.676E-10	6.674E-10	6.676E-10	6.784E-10	6.676E-10	6.568E-10	5.52
150	6.700E-10	6.534E-10	6.403E-10	6.701E-10	6.701E-10	6.532E-10	6.812E-10	6.812E-10	5.374E-10	6.701E-10	6.701E-10	6.699E-10	6.701E-10	6.811E-10	6.701E-10	6.592E-10	5.57
200	6.709E-10	6.542E-10	6.411E-10	6.710E-10	6.710E-10	6.541E-10	6.822E-10	6.822E-10	5.375E-10	6.709E-10	6.709E-10	6.708E-10	6.709E-10	6.821E-10	6.709E-10	6.600E-10	5.59
300	6.710E-10	6.542E-10	6.412E-10	6.710E-10	6.710E-10	6.541E-10	6.823E-10	6.823E-10	5.375E-10	6.710E-10	6.710E-10	6.708E-10	6.710E-10	6.822E-10	6.710E-10	6.601E-10	5.60
500	6.710E-10	6.543E-10	6.411E-10	6.711E-10	6.711E-10	6.542E-10	6.822E-10	6.822E-10	5.375E-10	6.711E-10	6.710E-10	6.709E-10	6.711E-10	6.821E-10	6.709E-10	6.601E-10	5.60
1 000	6.707E-10	6.540E-10	6.410E-10	6.708E-10	6.708E-10	6.539E-10	6.820E-10	6.820E-10	5.374E-10	6.708E-10	6.708E-10	6.706E-10	6.708E-10	6.820E-10	6.708E-10	6.599E-10	5.60
2 000	6.704E-10	6.537E-10	6.407E-10	6.705E-10	6.705E-10	6.536E-10	6.817E-10	6.817E-10	5.371E-10	6.705E-10	6.705E-10	6.703E-10	6.705E-10	6.817E-10	6.705E-10	6.596E-10	5.60
5 000	6.695E-10	6.529E-10	6.398E-10	6.696E-10	6.696E-10	6.527E-10	6.808E-10	6.808E-10	5.364E-10	6.696E-10	6.696E-10	6.694E-10	6.696E-10	6.810E-10	6.696E-10	6.587E-10	5.60
8 000	6.686E-10	6.520E-10	6.390E-10	6.687E-10	6.687E-10	6.519E-10	6.799E-10	6.799E-10	5.357E-10	6.687E-10	6.687E-10	6.685E-10	6.687E-10	6.800E-10	6.687E-10	6.578E-10	5.60
10 000	6.680E-10	6.514E-10	6.384E-10	6.681E-10	6.681E-10	6.513E-10	6.793E-10	6.793E-10	5.352E-10	6.681E-10	6.681E-10	6.679E-10	6.681E-10	6.793E-10	6.680E-10	6.572E-10	5.60
15 000	6.665E-10	6.499E-10	6.369E-10	6.666E-10	6.666E-10	6.498E-10	6.777E-10	6.777E-10	5.340E-10	6.666E-10	6.666E-10	6.664E-10	6.666E-10	6.779E-10	6.665E-10	6.558E-10	5.60
20 000	6.650E-10	6.484E-10	6.355E-10	6.651E-10	6.651E-10	6.483E-10	6.762E-10	6.762E-10	5.328E-10	6.651E-10	6.651E-10	6.649E-10	6.651E-10	6.764E-10	6.650E-10	6.543E-10	5.60
25 000	6.635E-10	6.470E-10	6.340E-10	6.636E-10	6.636E-10	6.469E-10	6.747E-10	6.747E-10	5.316E-10	6.636E-10	6.636E-10	6.634E-10	6.636E-10	6.748E-10	6.635E-10	6.528E-10	5.60
30 000	6.620E-10	6.455E-10	6.326E-10	6.621E-10	6.621E-10	6.454E-10	6.731E-10	6.731E-10	5.304E-10	6.621E-10	6.621E-10	6.619E-10	6.621E-10	6.733E-10	6.620E-10	6.513E-10	5.60
40 000	6.590E-10	6.426E-10	6.297E-10	6.591E-10	6.591E-10	6.425E-10	6.701E-10	6.701E-10	5.280E-10	6.591E-10	6.591E-10	6.589E-10	6.591E-10	6.705E-10	6.590E-10	6.484E-10	5.60
45 000	6.575E-10	6.411E-10	6.283E-10	6.576E-10	6.576E-10	6.410E-10	6.686E-10	6.686E-10	5.268E-10	6.576E-10	6.576E-10	6.574E-10	6.576E-10	6.687E-10	6.575E-10	6.469E-10	5.60
50 000	6.560E-10	6.397E-10	6.268E-10	6.561E-10	6.561E-10	6.396E-10	6.671E-10	6.671E-10	5.256E-10	6.561E-10	6.561E-10	6.559E-10	6.561E-10	6.672E-10	6.561E-10	6.454E-10	5.60
100 000	6.413E-10	6.253E-10	6.127E-10	6.414E-10	6.414E-10	6.252E-10	6.521E-10	6.521E-10	5.138E-10	6.414E-10	6.414E-10	6.412E-10	6.414E-10	6.540E-10	6.414E-10	6.311E-10	5.61
500 000	5.350E-10	5.217E-10	5.106E-10	5.351E-10	5.351E-10	5.216E-10	5.440E-10	5.440E-10	4.286E-10	5.352E-10	5.351E-10	5.349E-10	5.351E-10	5.565E-10	5.351E-10	5.272E-10	5.74
1 000 000	4.266E-10	4.159E-10	4.066E-10	4.266E-10	4.266E-10	4.159E-10	4.336E-10	4.336E-10	3.418E-10	4.268E-10	4.266E-10	4.265E-10	4.266E-10	4.463E-10	4.266E-10	4.204E-10	5.79

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 10. Relative difference from sample mean as a function of decay time for ^{93m}Nb atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 18. ^{93m}Nb half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	5.09024E+08	5.09013E+08	5.08896E+08	5.17218E+08	5.09000E+08	4.29200E+08
Uncertainty (s)	4.41806E+06	4.73354E+06	4.32000E+06	-	5.00000E+06	-

Sources: References 12, 13, 15, 20 and 21.

3.9. Time-dependent ^{94}Nb atom densities

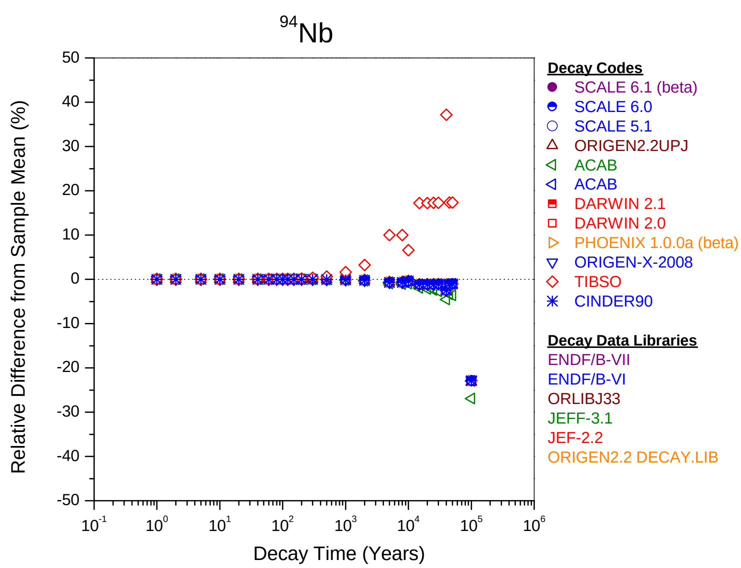
^{94}Nb is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of $2.03 \times 10^4 \pm 1.6 \times 10^3$ years and decays by beta-particle emission [20]. The ^{94}Nb half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, JEFF-3.1, ENDF/B-VI.8, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 19. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 20. In the table, the calculated ^{94}Nb atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{94}Nb using the evaluated decay codes/data libraries is illustrated in Figure 11. As seen in the figure, the ^{94}Nb atom density values obtained using TIBSO significantly differ from the corresponding values obtained with the other evaluated decay codes/libraries at long decay times.

Table 19. ^{94}Nb half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	6.40619E+11	6.40606E+11	6.30720E+11	6.40606E+11	6.40000E+11	6.40600E+11
Uncertainty (s)	5.04921E+10	5.04911E+10	7.77600E+10	-	5.00000E+10	-

Sources: References 12, 13, 15, 20 and 21.

Figure 11. Relative difference from sample mean as a function of decay time for ^{94}Nb atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 20. Decay calculation results for ^{94}Nb (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	0.00
1	6.215E-11	6.214E-11	6.214E-11	6.215E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.212E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	0.01
2	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.214E-11	6.212E-11	6.214E-11	6.214E-11	6.214E-11	6.487E-11	0.01
5	6.214E-11	6.213E-11	6.213E-11	6.214E-11	6.213E-11	6.213E-11	6.213E-11	6.213E-11	6.213E-11	6.213E-11	6.213E-11	6.212E-11	6.213E-11	6.214E-11	6.213E-11	6.213E-11	0.01
10	6.213E-11	6.212E-11	6.212E-11	6.213E-11	6.212E-11	6.212E-11	6.212E-11	6.212E-11	6.212E-11	6.212E-11	6.212E-11	6.211E-11	6.212E-11	6.213E-11	6.212E-11	6.212E-11	0.01
20	6.211E-11	6.210E-11	6.210E-11	6.211E-11	6.210E-11	6.210E-11	6.210E-11	6.210E-11	6.210E-11	6.210E-11	6.210E-11	6.208E-11	6.210E-11	6.212E-11	6.210E-11	6.210E-11	0.01
40	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.206E-11	6.204E-11	6.206E-11	6.210E-11	6.206E-11	6.206E-11	0.02
60	6.202E-11	6.202E-11	6.202E-11	6.202E-11	6.202E-11	6.201E-11	6.202E-11	6.202E-11	6.202E-11	6.202E-11	6.202E-11	6.200E-11	6.202E-11	6.206E-11	6.202E-11	6.202E-11	0.02
80	6.198E-11	6.197E-11	6.197E-11	6.198E-11	6.197E-11	6.197E-11	6.197E-11	6.197E-11	6.197E-11	6.197E-11	6.197E-11	6.196E-11	6.197E-11	6.202E-11	6.197E-11	6.198E-11	0.02
100	6.194E-11	6.193E-11	6.193E-11	6.194E-11	6.193E-11	6.193E-11	6.193E-11	6.193E-11	6.193E-11	6.193E-11	6.193E-11	6.191E-11	6.193E-11	6.197E-11	6.193E-11	6.193E-11	0.02
120	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.189E-11	6.187E-11	6.189E-11	6.193E-11	6.189E-11	6.189E-11	0.02
150	6.183E-11	6.183E-11	6.183E-11	6.183E-11	6.183E-11	6.182E-11	6.183E-11	6.183E-11	6.183E-11	6.183E-11	6.183E-11	6.181E-11	6.183E-11	6.189E-11	6.183E-11	6.183E-11	0.03
200	6.173E-11	6.172E-11	6.172E-11	6.173E-11	6.172E-11	6.171E-11	6.172E-11	6.172E-11	6.172E-11	6.172E-11	6.172E-11	6.170E-11	6.172E-11	6.183E-11	6.172E-11	6.173E-11	0.05
300	6.152E-11	6.151E-11	6.151E-11	6.152E-11	6.151E-11	6.150E-11	6.151E-11	6.151E-11	6.151E-11	6.151E-11	6.151E-11	6.149E-11	6.151E-11	6.172E-11	6.151E-11	6.152E-11	0.09
500	6.110E-11	6.109E-11	6.109E-11	6.110E-11	6.109E-11	6.108E-11	6.109E-11	6.109E-11	6.109E-11	6.109E-11	6.109E-11	6.108E-11	6.109E-11	6.151E-11	6.109E-11	6.112E-11	0.18
1 000	6.006E-11	6.006E-11	6.006E-11	6.006E-11	6.006E-11	6.003E-11	6.006E-11	6.006E-11	6.006E-11	6.006E-11	6.006E-11	6.004E-11	6.006E-11	6.109E-11	6.006E-11	6.012E-11	0.45
2 000	5.805E-11	5.804E-11	5.804E-11	5.805E-11	5.804E-11	5.798E-11	5.804E-11	5.804E-11	5.804E-11	5.804E-11	5.804E-11	5.803E-11	5.804E-11	6.006E-11	5.804E-11	5.817E-11	0.90
5 000	5.239E-11	5.239E-11	5.238E-11	5.239E-11	5.239E-11	5.225E-11	5.239E-11	5.239E-11	5.239E-11	5.240E-11	5.239E-11	5.238E-11	5.239E-11	5.804E-11	5.239E-11	5.276E-11	2.77
8 000	4.729E-11	4.729E-11	4.728E-11	4.729E-11	4.729E-11	4.709E-11	4.729E-11	4.729E-11	4.729E-11	4.730E-11	4.729E-11	4.728E-11	4.729E-11	5.239E-11	4.729E-11	4.761E-11	2.78
10 000	4.417E-11	4.417E-11	4.415E-11	4.417E-11	4.417E-11	4.393E-11	4.417E-11	4.417E-11	4.417E-11	4.418E-11	4.417E-11	4.415E-11	4.417E-11	4.729E-11	4.417E-11	4.436E-11	1.83
15 000	3.724E-11	3.723E-11	3.722E-11	3.724E-11	3.724E-11	3.694E-11	3.724E-11	3.724E-11	3.724E-11	3.725E-11	3.723E-11	3.722E-11	3.723E-11	4.417E-11	3.724E-11	3.768E-11	4.77
20 000	3.139E-11	3.139E-11	3.137E-11	3.139E-11	3.139E-11	3.106E-11	3.139E-11	3.139E-11	3.139E-11	3.141E-11	3.139E-11	3.138E-11	3.139E-11	3.723E-11	3.139E-11	3.176E-11	4.78
25 000	2.646E-11	2.646E-11	2.644E-11	2.646E-11	2.646E-11	2.611E-11	2.647E-11	2.647E-11	2.647E-11	2.648E-11	2.646E-11	2.646E-11	2.646E-11	3.139E-11	2.647E-11	2.677E-11	4.79
30 000	2.231E-11	2.231E-11	2.229E-11	2.231E-11	2.231E-11	2.195E-11	2.231E-11	2.231E-11	2.231E-11	2.233E-11	2.231E-11	2.230E-11	2.231E-11	2.646E-11	2.231E-11	2.256E-11	4.80
40 000	1.586E-11	1.586E-11	1.584E-11	1.586E-11	1.586E-11	1.552E-11	1.586E-11	1.586E-11	1.586E-11	1.587E-11	1.586E-11	1.585E-11	1.586E-11	2.231E-11	1.586E-11	1.626E-11	10.30
45 000	1.337E-11	1.337E-11	1.335E-11	1.337E-11	1.337E-11	1.305E-11	1.337E-11	1.337E-11	1.337E-11	1.338E-11	1.337E-11	1.336E-11	1.337E-11	1.586E-11	1.337E-11	1.351E-11	4.84
50 000	1.127E-11	1.127E-11	1.125E-11	1.127E-11	1.127E-11	1.097E-11	1.127E-11	1.127E-11	1.127E-11	1.128E-11	1.127E-11	1.127E-11	1.127E-11	1.337E-11	1.127E-11	1.139E-11	4.85
100 000	2.044E-12	2.043E-12	2.037E-12	2.044E-12	2.044E-12	1.937E-12	2.044E-12	2.044E-12	2.044E-12	2.049E-12	2.043E-12	2.043E-12	2.043E-12	1.127E-11	2.044E-12	2.652E-12	89.91

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.10. Time-dependent ^{93}Mo atom densities

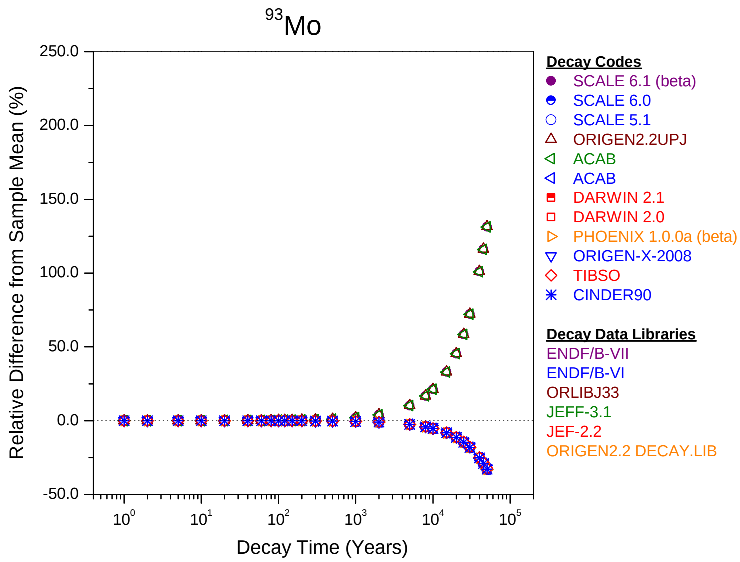
^{93}Mo is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of $4.0 \times 10^3 \pm 800$ years and decays by electron capture [20]. The ^{93}Mo half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 21. As seen in the table, the most recently evaluated ^{93}Mo half-life value is approximately 14% greater than the previous evaluations. The error associated with the ^{93}Mo half-life values is ~ 20%. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 22. In the table, the calculated ^{93}Mo atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{93}Mo using the evaluated decay codes/data libraries is illustrated in Figure 12. The dispersion of the results observed at long decay times (e.g. RSD ≈ 70% at 5×10^4 years) may be attributed to the different half-life values used by the evaluated decay codes/libraries.

Table 21. ^{93}Mo half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	1.26230E+11	1.10449E+11	1.26228E+11	1.10449E+11	1.26230E+11	1.10400E+11
Uncertainty (s)	2.52460E+10	2.20898E+10	2.52455E+10	-	2.52460E+10	-

Sources: References 12–14, 20 and 21.

Figure 12. Relative difference from sample mean as a function of decay time for ^{93}Mo atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 22. Decay calculation results for ^{93}Mo (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	0.00
1	1.147E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	1.147E-14	1.148E-14	1.148E-14	1.148E-14	1.148E-14	0.03
2	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	0.01
5	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	1.146E-14	1.147E-14	1.147E-14	1.147E-14	1.147E-14	0.02
10	1.145E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	1.145E-14	1.146E-14	1.146E-14	1.146E-14	1.146E-14	0.03
20	1.143E-14	1.144E-14	1.144E-14	1.143E-14	1.143E-14	1.144E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	1.143E-14	0.03
40	1.139E-14	1.140E-14	1.140E-14	1.139E-14	1.139E-14	1.140E-14	1.139E-14	1.139E-14	1.139E-14	1.139E-14	1.139E-14	1.138E-14	1.139E-14	1.139E-14	1.139E-14	1.139E-14	0.05
60	1.134E-14	1.136E-14	1.136E-14	1.134E-14	1.134E-14	1.136E-14	1.134E-14	1.134E-14	1.134E-14	1.134E-14	1.134E-14	1.134E-14	1.134E-14	1.134E-14	1.134E-14	1.135E-14	0.07
80	1.130E-14	1.132E-14	1.132E-14	1.130E-14	1.130E-14	1.132E-14	1.130E-14	1.130E-14	1.130E-14	1.130E-14	1.130E-14	1.129E-14	1.130E-14	1.130E-14	1.130E-14	1.130E-14	0.09
100	1.125E-14	1.128E-14	1.128E-14	1.125E-14	1.125E-14	1.128E-14	1.125E-14	1.125E-14	1.125E-14	1.125E-14	1.125E-14	1.125E-14	1.125E-14	1.125E-14	1.125E-14	1.126E-14	0.11
120	1.121E-14	1.124E-14	1.124E-14	1.121E-14	1.121E-14	1.124E-14	1.121E-14	1.121E-14	1.121E-14	1.121E-14	1.121E-14	1.121E-14	1.121E-14	1.121E-14	1.121E-14	1.122E-14	0.12
150	1.114E-14	1.118E-14	1.118E-14	1.114E-14	1.114E-14	1.118E-14	1.114E-14	1.114E-14	1.114E-14	1.114E-14	1.114E-14	1.114E-14	1.114E-14	1.114E-14	1.114E-14	1.115E-14	0.16
200	1.103E-14	1.109E-14	1.109E-14	1.103E-14	1.103E-14	1.109E-14	1.103E-14	1.103E-14	1.103E-14	1.103E-14	1.103E-14	1.103E-14	1.103E-14	1.103E-14	1.103E-14	1.104E-14	0.22
300	1.081E-14	1.090E-14	1.090E-14	1.082E-14	1.082E-14	1.090E-14	1.082E-14	1.082E-14	1.082E-14	1.082E-14	1.082E-14	1.081E-14	1.082E-14	1.082E-14	1.082E-14	1.083E-14	0.32
500	1.039E-14	1.053E-14	1.053E-14	1.040E-14	1.040E-14	1.053E-14	1.040E-14	1.040E-14	1.040E-14	1.040E-14	1.040E-14	1.039E-14	1.040E-14	1.040E-14	1.040E-14	1.042E-14	0.54
1 000	9.414E-15	9.652E-15	9.652E-15	9.415E-15	9.416E-15	9.651E-15	9.416E-15	9.416E-15	9.416E-15	9.417E-15	9.416E-15	9.413E-15	9.416E-15	9.417E-15	9.416E-15	9.463E-15	1.06
2 000	7.722E-15	8.116E-15	8.116E-15	7.723E-15	7.724E-15	8.116E-15	7.724E-15	7.724E-15	7.724E-15	7.726E-15	7.724E-15	7.722E-15	7.724E-15	7.726E-15	7.724E-15	7.802E-15	2.14
5 000	4.261E-15	4.825E-15	4.826E-15	4.262E-15	4.264E-15	4.825E-15	4.264E-15	4.264E-15	4.263E-15	4.267E-15	4.264E-15	4.263E-15	4.264E-15	4.267E-15	4.264E-15	4.376E-15	5.46
8 000	2.352E-15	2.869E-15	2.870E-15	2.352E-15	2.354E-15	2.869E-15	2.354E-15	2.354E-15	2.353E-15	2.356E-15	2.354E-15	2.353E-15	2.354E-15	2.357E-15	2.354E-15	2.457E-15	8.93
1 0000	1.582E-15	2.029E-15	2.029E-15	1.582E-15	1.584E-15	2.028E-15	1.584E-15	1.584E-15	1.583E-15	1.586E-15	1.584E-15	1.583E-15	1.584E-15	1.586E-15	1.584E-15	1.673E-15	11.32
15 000	5.875E-16	8.529E-16	8.531E-16	5.876E-16	5.885E-16	8.526E-16	5.885E-16	5.885E-16	5.879E-16	5.897E-16	5.883E-16	5.882E-16	5.883E-16	5.897E-16	5.885E-16	6.413E-16	17.56
20 000	2.181E-16	3.586E-16	3.587E-16	2.182E-16	2.186E-16	3.584E-16	2.186E-16	2.186E-16	2.183E-16	2.192E-16	2.185E-16	2.185E-16	2.185E-16	2.192E-16	2.186E-16	2.466E-16	24.17
25 000	8.099E-17	1.507E-16	1.508E-16	8.100E-17	8.122E-17	1.507E-16	8.123E-17	8.123E-17	8.107E-17	8.149E-17	8.118E-17	8.116E-17	8.118E-17	8.149E-17	8.122E-17	9.511E-17	31.12
30 000	3.007E-17	6.338E-17	6.341E-17	3.008E-17	3.017E-17	6.333E-17	3.018E-17	3.018E-17	3.010E-17	3.029E-17	3.015E-17	3.015E-17	3.015E-17	3.030E-17	3.017E-17	3.681E-17	38.42
40 000	4.146E-18	1.120E-17	1.121E-17	4.146E-18	4.164E-18	1.119E-17	4.165E-18	4.165E-18	4.151E-18	4.186E-18	4.161E-18	4.160E-18	4.161E-18	4.187E-18	4.165E-18	5.570E-18	53.79
45 000	1.539E-18	4.709E-18	4.713E-18	1.540E-18	1.547E-18	4.704E-18	1.547E-18	1.547E-18	1.541E-18	1.556E-18	1.546E-18	1.545E-18	1.546E-18	1.556E-18	1.547E-18	2.179E-18	61.80
50 000	5.715E-19	1.980E-18	1.981E-18	5.716E-19	5.747E-19	1.977E-18	5.748E-19	5.748E-19	5.724E-19	5.785E-19	5.741E-19	5.740E-19	5.741E-19	5.786E-19	5.748E-19	8.555E-19	69.94

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.11. Time-dependent ^{99}Tc atom densities

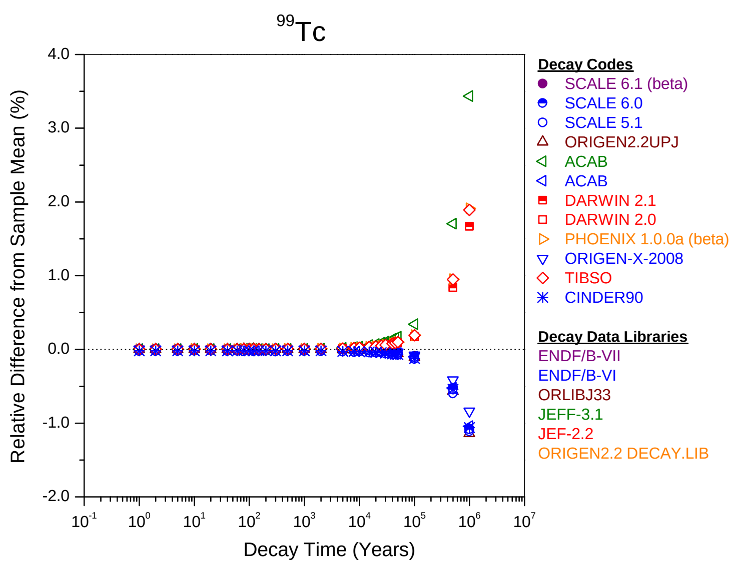
^{99}Tc is a fission product nuclide important for burn-up credit criticality analyses and for radiological dose assessments. This nuclide has a half-life of $2.111 \times 10^5 \pm 1.2 \times 10^3$ years and decays by beta-particle emission [20]. A very small ^{99}Tc quantity is formed at short time after fuel discharge as a result of ^{99}Mo ($T_{1/2}$ = 65.94 ± 0.01 hours) beta decay. The ^{99}Tc half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 23. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 24. In the table, the calculated ^{99}Tc atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{99}Tc using the evaluated decay codes/data libraries is illustrated in Figure 13. A very small dispersion of the calculated ^{99}Tc atom densities is observed at long decay times (e.g. RSD ≈ 1.6% at 10^6 years), which is consistent with the differences in the half-life values used.

Table 23. ^{99}Tc half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	6.66180E+12	6.66167E+12	6.75318E+12	6.72163E+12	6.66000E+12	6.72200E+12
Uncertainty (s)	3.78691E+10	3.78683E+10	2.52455E+11	-	4.00000E+10	-

Sources: References 12, 13, 15, 20 and 21.

Figure 13. Relative difference from sample mean as a function of decay time for ^{99}Tc atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 24. Decay calculation results for ^{99}Tc (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	6.673E-05	0.00
1	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.691E-05	6.693E-05	6.693E-05	6.691E-05	6.692E-05	0.01
2	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.691E-05	6.693E-05	6.693E-05	6.691E-05	6.692E-05	0.01
5	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.691E-05	6.693E-05	6.693E-05	6.691E-05	6.692E-05	0.01
10	6.693E-05	6.692E-05	6.692E-05	6.693E-05	6.692E-05	6.693E-05	6.693E-05	6.693E-05	6.693E-05	6.692E-05	6.692E-05	6.691E-05	6.692E-05	6.692E-05	6.691E-05	6.692E-05	0.01
20	6.693E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.691E-05	6.692E-05	6.692E-05	6.691E-05	6.692E-05	0.01
40	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.690E-05	6.692E-05	6.692E-05	6.690E-05	6.692E-05	0.01
60	6.692E-05	6.691E-05	6.691E-05	6.692E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.690E-05	6.691E-05	6.691E-05	6.690E-05	6.691E-05	0.01
80	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.689E-05	6.691E-05	6.691E-05	6.689E-05	6.691E-05	0.01
100	6.691E-05	6.691E-05	6.690E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.691E-05	6.690E-05	6.689E-05	6.690E-05	6.691E-05	6.689E-05	6.690E-05	0.01
120	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.690E-05	6.688E-05	6.690E-05	6.690E-05	6.689E-05	6.690E-05	0.01
150	6.690E-05	6.689E-05	6.689E-05	6.690E-05	6.689E-05	6.689E-05	6.689E-05	6.689E-05	6.689E-05	6.689E-05	6.689E-05	6.688E-05	6.689E-05	6.689E-05	6.688E-05	6.689E-05	0.01
200	6.689E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.688E-05	6.687E-05	6.688E-05	6.688E-05	6.687E-05	6.688E-05	0.01
300	6.687E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.686E-05	6.684E-05	6.686E-05	6.686E-05	6.685E-05	6.686E-05	0.01
500	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.682E-05	6.680E-05	6.682E-05	6.682E-05	6.680E-05	6.682E-05	0.01
1 000	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.671E-05	6.669E-05	6.671E-05	6.671E-05	6.669E-05	6.671E-05	0.01
2 000	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.649E-05	6.647E-05	6.649E-05	6.649E-05	6.647E-05	6.649E-05	0.01
5 000	6.584E-05	6.584E-05	6.584E-05	6.584E-05	6.584E-05	6.585E-05	6.585E-05	6.585E-05	6.585E-05	6.584E-05	6.584E-05	6.582E-05	6.584E-05	6.585E-05	6.582E-05	6.584E-05	0.01
8 000	6.520E-05	6.519E-05	6.519E-05	6.519E-05	6.519E-05	6.522E-05	6.521E-05	6.521E-05	6.521E-05	6.519E-05	6.519E-05	6.517E-05	6.519E-05	6.521E-05	6.518E-05	6.520E-05	0.02
10 000	6.477E-05	6.477E-05	6.476E-05	6.477E-05	6.477E-05	6.479E-05	6.478E-05	6.478E-05	6.478E-05	6.477E-05	6.476E-05	6.475E-05	6.476E-05	6.478E-05	6.475E-05	6.477E-05	0.02
15 000	6.371E-05	6.371E-05	6.371E-05	6.371E-05	6.371E-05	6.375E-05	6.374E-05	6.374E-05	6.374E-05	6.371E-05	6.371E-05	6.369E-05	6.371E-05	6.374E-05	6.370E-05	6.372E-05	0.03
20 000	6.268E-05	6.267E-05	6.267E-05	6.267E-05	6.267E-05	6.273E-05	6.271E-05	6.271E-05	6.271E-05	6.268E-05	6.267E-05	6.266E-05	6.267E-05	6.271E-05	6.266E-05	6.268E-05	0.03
25 000	6.166E-05	6.165E-05	6.165E-05	6.165E-05	6.165E-05	6.172E-05	6.169E-05	6.169E-05	6.170E-05	6.166E-05	6.165E-05	6.164E-05	6.165E-05	6.170E-05	6.164E-05	6.167E-05	0.04
30 000	6.065E-05	6.065E-05	6.065E-05	6.065E-05	6.065E-05	6.073E-05	6.070E-05	6.070E-05	6.070E-05	6.065E-05	6.065E-05	6.063E-05	6.065E-05	6.070E-05	6.064E-05	6.067E-05	0.05
40 000	5.869E-05	5.869E-05	5.869E-05	5.869E-05	5.869E-05	5.879E-05	5.875E-05	5.875E-05	5.876E-05	5.869E-05	5.869E-05	5.867E-05	5.869E-05	5.876E-05	5.868E-05	5.871E-05	0.07
45 000	5.774E-05	5.773E-05	5.773E-05	5.773E-05	5.773E-05	5.785E-05	5.780E-05	5.780E-05	5.781E-05	5.774E-05	5.773E-05	5.772E-05	5.773E-05	5.781E-05	5.772E-05	5.776E-05	0.07
50 000	5.680E-05	5.679E-05	5.679E-05	5.679E-05	5.679E-05	5.692E-05	5.687E-05	5.687E-05	5.688E-05	5.680E-05	5.679E-05	5.678E-05	5.679E-05	5.688E-05	5.678E-05	5.682E-05	0.08
100 000	4.820E-05	4.819E-05	4.819E-05	4.819E-05	4.820E-05	4.841E-05	4.833E-05	4.833E-05	4.834E-05	4.821E-05	4.819E-05	4.818E-05	4.819E-05	4.834E-05	4.818E-05	4.824E-05	0.16
500 000	1.296E-05	1.296E-05	1.295E-05	1.296E-05	1.296E-05	1.325E-05	1.314E-05	1.314E-05	1.315E-05	1.297E-05	1.296E-05	1.295E-05	1.296E-05	1.315E-05	1.296E-05	1.303E-05	0.80
1 000 000	2.509E-06	2.509E-06	2.507E-06	2.509E-06	2.510E-06	2.623E-06	2.579E-06	2.579E-06	2.585E-06	2.515E-06	2.509E-06	2.508E-06	2.509E-06	2.584E-06	2.509E-06	2.536E-06	1.60

[a] SCALE 6/ORIGEN decay data.

[b] JEFF-3.1 decay data.

3.12. Time-dependent ^{107}Pd atom densities

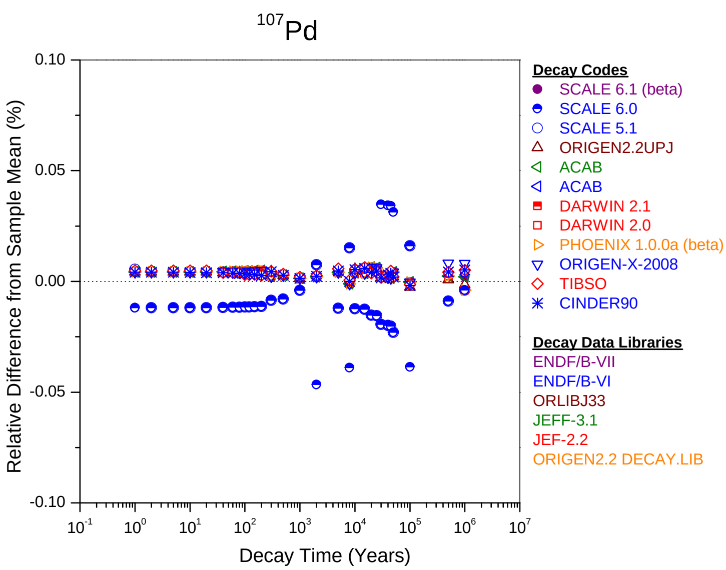
^{107}Pd is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of $6.5\times10^6 \pm 3\times10^5$ years and decays by beta-particle emission [20]. The ^{107}Pd half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 25. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 26. In the table, the calculated ^{107}Pd atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{107}Pd using the evaluated decay codes/data libraries is illustrated in Figure 14. All ^{107}Pd atom density results at any given decay time are practically identical.

Table 25. ^{107}Pd half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	2.05124E+14	2.05120E+14	2.05120E+14	2.05124E+14	2.05000E+14	2.05000E+14
Uncertainty (s)	9.46728E+12	9.46708E+12	9.46708E+12	-	1.00000E+13	-

Sources: References 12, 13, 15, 20 and 21.

Figure 14. Relative difference from sample mean as a function of decay time for ^{107}Pd atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 26. Decay calculation results for ^{107}Pd (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.00
1	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
2	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
5	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
10	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
20	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
40	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
60	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
80	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
100	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
120	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
150	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
200	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
300	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
500	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
1 000	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.00
2 000	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	1.849E-05	1.850E-05	1.850E-05	1.850E-05	1.850E-05	0.01
5 000	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	0.01
8 000	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	1.848E-05	1.849E-05	1.849E-05	1.849E-05	1.849E-05	0.01
10 000	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	1.848E-05	0.01
15 000	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	1.847E-05	0.01
20 000	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	1.846E-05	0.01
25 000	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	1.845E-05	0.01
30 000	1.844E-05	1.844E-05	1.844E-05	1.845E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	1.844E-05	0.01
40 000	1.842E-05	1.842E-05	1.842E-05	1.843E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	1.842E-05	0.01
45 000	1.841E-05	1.841E-05	1.841E-05	1.842E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	0.01
50 000	1.840E-05	1.840E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.841E-05	1.840E-05	1.840E-05	1.840E-05	1.840E-05	1.840E-05	1.840E-05	0.02
100 000	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	1.830E-05	1.831E-05	1.831E-05	1.831E-05	1.831E-05	0.01
500 000	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	1.754E-05	0.01
1 000 000	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	1.663E-05	0.00

[a] SCALE 6/ORIGEN decay data.

[b] JEFF-3.1 decay data.

3.13. Time-dependent ^{126}Sn atom densities

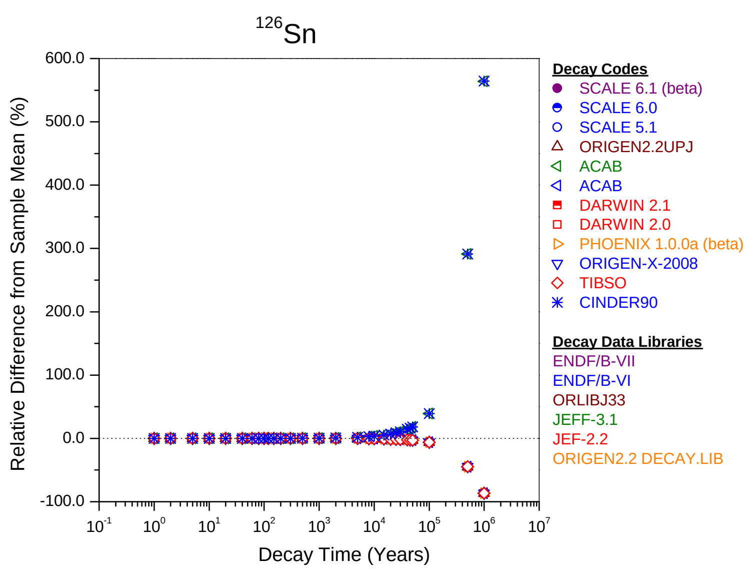
^{126}Sn is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life value of $2.30\times10^5 \pm 1.4\times10^3$ years and decays by beta-particle emission [20]. The ^{126}Sn half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 27. As seen in the table, there is a significant difference between most recently evaluated ^{126}Sn half-life values and previous evaluations, which provided only an approximate value [20]. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 28. In the table, the calculated ^{126}Sn atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{126}Sn using the evaluated decay codes/data libraries is illustrated in Figure 15. The significant dispersion of the calculation results observed at long decay times (e.g. RSD ≈ 165% at 10^6 years) is consistent with the variability of the ^{126}Sn half-life values used by the evaluated decay codes.

Table 27. ^{126}Sn half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	7.25824E+12	3.15569E+12	7.25809E+12	3.15569E+12	3.15600E+12	3.15600E+12
Uncertainty (s)	4.41806E+11	-	4.41797E+11	-	-	-

Sources: References 12, 13, 15, 20 and 21.

Figure 15. Relative difference from sample mean as a function of decay time for ^{126}Sn atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 28. Decay calculation results for ^{126}Sn (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.00
1	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.01
2	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.01
5	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.01
10	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.00
20	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.00
40	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.284E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.02
60	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.284E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	0.02
80	1.284E-06	1.285E-06	1.284E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.285E-06	0.03
100	1.284E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.284E-06	0.02
120	1.284E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.284E-06	0.02
150	1.284E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.284E-06	1.285E-06	1.284E-06	0.03
200	1.283E-06	1.284E-06	1.283E-06	1.283E-06	1.283E-06	1.284E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.284E-06	1.283E-06	0.03
300	1.283E-06	1.284E-06	1.283E-06	1.283E-06	1.283E-06	1.284E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.283E-06	1.282E-06	1.283E-06	1.283E-06	1.284E-06	1.283E-06	0.04
500	1.281E-06	1.283E-06	1.281E-06	1.281E-06	1.281E-06	1.283E-06	1.281E-06	1.281E-06	1.281E-06	1.281E-06	1.281E-06	1.280E-06	1.281E-06	1.281E-06	1.283E-06	1.281E-06	0.07
1 000	1.276E-06	1.281E-06	1.276E-06	1.276E-06	1.276E-06	1.281E-06	1.276E-06	1.276E-06	1.276E-06	1.276E-06	1.276E-06	1.276E-06	1.276E-06	1.276E-06	1.281E-06	1.277E-06	0.14
2 000	1.267E-06	1.277E-06	1.268E-06	1.268E-06	1.268E-06	1.278E-06	1.268E-06	1.268E-06	1.268E-06	1.268E-06	1.268E-06	1.267E-06	1.268E-06	1.268E-06	1.277E-06	1.269E-06	0.28
5 000	1.241E-06	1.266E-06	1.241E-06	1.241E-06	1.241E-06	1.266E-06	1.241E-06	1.241E-06	1.241E-06	1.241E-06	1.241E-06	1.241E-06	1.241E-06	1.241E-06	1.266E-06	1.246E-06	0.72
8 000	1.216E-06	1.255E-06	1.216E-06	1.216E-06	1.216E-06	1.255E-06	1.216E-06	1.216E-06	1.216E-06	1.216E-06	1.216E-06	1.216E-06	1.216E-06	1.216E-06	1.255E-06	1.224E-06	1.15
10 000	1.199E-06	1.247E-06	1.199E-06	1.199E-06	1.199E-06	1.247E-06	1.199E-06	1.199E-06	1.199E-06	1.199E-06	1.199E-06	1.199E-06	1.199E-06	1.199E-06	1.247E-06	1.209E-06	1.44
15 000	1.158E-06	1.228E-06	1.158E-06	1.158E-06	1.158E-06	1.228E-06	1.158E-06	1.158E-06	1.158E-06	1.158E-06	1.158E-06	1.158E-06	1.158E-06	1.158E-06	1.228E-06	1.172E-06	2.17
20 000	1.119E-06	1.210E-06	1.119E-06	1.119E-06	1.119E-06	1.210E-06	1.119E-06	1.119E-06	1.119E-06	1.119E-06	1.119E-06	1.119E-06	1.119E-06	1.119E-06	1.210E-06	1.137E-06	2.91
25 000	1.081E-06	1.192E-06	1.081E-06	1.081E-06	1.081E-06	1.192E-06	1.081E-06	1.081E-06	1.081E-06	1.081E-06	1.081E-06	1.080E-06	1.081E-06	1.081E-06	1.192E-06	1.103E-06	3.66
30 000	1.044E-06	1.174E-06	1.044E-06	1.044E-06	1.044E-06	1.174E-06	1.044E-06	1.044E-06	1.044E-06	1.044E-06	1.044E-06	1.044E-06	1.044E-06	1.044E-06	1.174E-06	1.070E-06	4.42
40 000	9.740E-07	1.139E-06	9.740E-07	9.740E-07	9.740E-07	1.139E-06	9.740E-07	9.740E-07	9.740E-07	9.742E-07	9.740E-07	9.737E-07	9.740E-07	9.742E-07	1.139E-06	1.007E-06	5.95
45 000	9.408E-07	1.122E-06	9.408E-07	9.408E-07	9.408E-07	1.122E-06	9.408E-07	9.408E-07	9.409E-07	9.410E-07	9.408E-07	9.405E-07	9.408E-07	9.410E-07	1.122E-06	9.771E-07	6.74
50 000	9.087E-07	1.105E-06	9.088E-07	9.088E-07	9.088E-07	1.105E-06	9.088E-07	9.088E-07	9.088E-07	9.090E-07	9.087E-07	9.085E-07	9.087E-07	9.090E-07	1.105E-06	9.481E-07	7.52
100 000	6.425E-07	9.508E-07	6.426E-07	6.426E-07	6.426E-07	9.508E-07	6.426E-07	6.426E-07	6.427E-07	6.429E-07	6.426E-07	6.424E-07	6.426E-07	6.429E-07	9.508E-07	7.043E-07	15.89
500 000	4.015E-08	2.848E-07	4.017E-08	4.015E-08	4.016E-08	2.848E-07	4.017E-08	4.017E-08	4.018E-08	4.026E-08	4.015E-08	4.014E-08	4.015E-08	4.026E-08	2.848E-07	8.910E-08	99.70
1 000 000	1.254E-09	6.310E-08	1.256E-09	1.254E-09	1.255E-09	6.311E-08	1.255E-09	1.255E-09	1.256E-09	1.261E-09	1.254E-09	1.254E-09	1.254E-09	1.261E-09	6.313E-08	1.363E-08	164.82

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.14. Time-dependent ^{126m}Sb atom densities

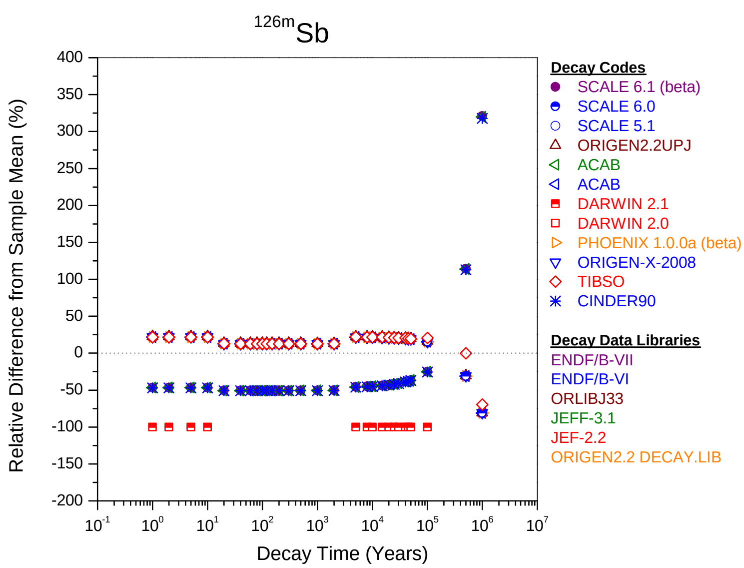
^{126m}Sb is a metastable isomer important for radiological dose assessments. This isomer, which has a half-life of 19.15 ± 0.08 minutes and decays by beta-particle emission and isomeric transition [20], is formed as a result of ^{126}Sn beta decay (see Section 3.13). The ^{126m}Sb half-life values and the uncertainties associated with the half-life values in ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 29. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 30. In the table, the calculated ^{126m}Sb atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{126m}Sb using the evaluated decay codes/data libraries is illustrated in Figure 16. The large dispersion of the ^{126m}Sb atom density results for long decay times (e.g. RSD ≈ 145% at 10^6 years) may be attributed to the variability of the ^{126}Sn half-life values utilised by the evaluated decay codes/libraries.

Table 29. ^{126m}Sb half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	1.14900E+03	1.14000E+03	1.14600E+03	1.14000E+03	1.14900+03	1.14000E+03
Uncertainty (s)	4.80000E+00	1.80000E+01	1.20000E+01	-	5.00000E+00	-

Sources: References 12, 13, 15, 20 and 21.

Figure 16. Relative difference from sample mean as a function of decay time for ^{126m}Sb atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 30. Decay calculation results for ^{126m}Sb (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	3.176E-13	0.00
1	4.643E-16	2.035E-16	4.679E-16	4.643E-16	4.643E-16	2.029E-16	0.000E+00	4.643E-16	4.642E-16	4.643E-16	4.643E-16	4.642E-16	4.643E-16	4.634E-16	2.019E-16	3.812E-16	38.69
2	4.643E-16	2.035E-16	4.679E-16	4.643E-16	4.643E-16	2.029E-16	0.000E+00	4.643E-16	4.642E-16	4.643E-16	4.643E-16	4.642E-16	4.643E-16	4.634E-16	2.019E-16	3.812E-16	38.69
5	4.643E-16	2.035E-16	4.679E-16	4.643E-16	4.643E-16	2.029E-16	0.000E+00	4.643E-16	4.642E-16	4.643E-16	4.643E-16	4.642E-16	4.643E-16	4.634E-16	2.019E-16	3.812E-16	38.69
10	4.643E-16	2.035E-16	4.679E-16	4.643E-16	4.642E-16	2.029E-16	0.000E+00	4.642E-16	4.642E-16	4.643E-16	4.643E-16	4.641E-16	4.643E-16	4.634E-16	2.018E-16	3.812E-16	38.69
20	4.642E-16	2.035E-16	4.678E-16	4.643E-16	4.642E-16	2.029E-16	4.642E-16	4.642E-16	4.642E-16	4.642E-16	4.642E-16	4.641E-16	4.642E-16	4.650E-16	2.018E-16	4.122E-16	23.03
40	4.642E-16	2.034E-16	4.678E-16	4.642E-16	4.641E-16	2.029E-16	4.641E-16	4.641E-16	4.641E-16	4.642E-16	4.642E-16	4.640E-16	4.642E-16	4.641E-16	2.018E-16	4.121E-16	23.03
60	4.641E-16	2.034E-16	4.677E-16	4.641E-16	4.641E-16	2.029E-16	4.641E-16	4.641E-16	4.640E-16	4.641E-16	4.641E-16	4.640E-16	4.641E-16	4.640E-16	2.018E-16	4.120E-16	23.02
80	4.640E-16	2.034E-16	4.676E-16	4.641E-16	4.640E-16	2.029E-16	4.640E-16	4.640E-16	4.640E-16	4.640E-16	4.640E-16	4.639E-16	4.640E-16	4.640E-16	2.018E-16	4.120E-16	23.02
100	4.640E-16	2.034E-16	4.676E-16	4.640E-16	4.640E-16	2.029E-16	4.640E-16	4.640E-16	4.639E-16	4.640E-16	4.640E-16	4.639E-16	4.640E-16	4.639E-16	2.018E-16	4.119E-16	23.02
120	4.639E-16	2.034E-16	4.675E-16	4.639E-16	4.639E-16	2.029E-16	4.639E-16	4.639E-16	4.639E-16	4.639E-16	4.639E-16	4.638E-16	4.639E-16	4.639E-16	2.018E-16	4.119E-16	23.02
150	4.638E-16	2.034E-16	4.674E-16	4.638E-16	4.638E-16	2.028E-16	4.638E-16	4.638E-16	4.638E-16	4.638E-16	4.638E-16	4.637E-16	4.638E-16	4.640E-16	2.018E-16	4.118E-16	23.02
200	4.637E-16	2.033E-16	4.673E-16	4.637E-16	4.636E-16	2.028E-16	4.636E-16	4.636E-16	4.636E-16	4.637E-16	4.637E-16	4.635E-16	4.637E-16	4.638E-16	2.017E-16	4.117E-16	23.01
300	4.633E-16	2.033E-16	4.669E-16	4.634E-16	4.633E-16	2.027E-16	4.633E-16	4.633E-16	4.633E-16	4.633E-16	4.633E-16	4.632E-16	4.633E-16	4.633E-16	2.017E-16	4.114E-16	23.00
500	4.627E-16	2.032E-16	4.663E-16	4.627E-16	4.627E-16	2.026E-16	4.627E-16	4.627E-16	4.626E-16	4.627E-16	4.627E-16	4.626E-16	4.627E-16	4.628E-16	2.015E-16	4.109E-16	22.99
1 000	4.611E-16	2.029E-16	4.647E-16	4.611E-16	4.611E-16	2.023E-16	4.611E-16	4.611E-16	4.610E-16	4.611E-16	4.611E-16	4.610E-16	4.611E-16	4.613E-16	2.012E-16	4.095E-16	22.95
2 000	4.579E-16	2.022E-16	4.615E-16	4.579E-16	4.579E-16	2.017E-16	4.579E-16	4.579E-16	4.579E-16	4.579E-16	4.579E-16	4.578E-16	4.579E-16	4.583E-16	2.006E-16	4.069E-16	22.87
5 000	4.485E-16	2.004E-16	4.520E-16	4.485E-16	4.485E-16	1.999E-16	0.000E+00	4.485E-16	4.484E-16	4.485E-16	4.485E-16	4.484E-16	4.485E-16	4.496E-16	1.988E-16	3.691E-16	38.41
8 000	4.392E-16	1.986E-16	4.427E-16	4.393E-16	4.392E-16	1.981E-16	0.000E+00	4.392E-16	4.392E-16	4.393E-16	4.393E-16	4.391E-16	4.393E-16	4.404E-16	1.970E-16	3.620E-16	38.23
10 000	4.332E-16	1.974E-16	4.366E-16	4.332E-16	4.332E-16	1.969E-16	0.000E+00	4.332E-16	4.332E-16	4.332E-16	4.332E-16	4.331E-16	4.332E-16	4.339E-16	1.959E-16	3.573E-16	38.11
15 000	4.184E-16	1.945E-16	4.217E-16	4.185E-16	4.184E-16	1.940E-16	0.000E+00	4.184E-16	4.184E-16	4.185E-16	4.184E-16	4.183E-16	4.184E-16	4.203E-16	1.929E-16	3.459E-16	37.82
20 000	4.042E-16	1.916E-16	4.073E-16	4.042E-16	4.042E-16	1.911E-16	0.000E+00	4.042E-16	4.042E-16	4.042E-16	4.042E-16	4.041E-16	4.042E-16	4.060E-16	1.900E-16	3.349E-16	37.53
25 000	3.904E-16	1.887E-16	3.935E-16	3.904E-16	3.904E-16	1.882E-16	0.000E+00	3.904E-16	3.904E-16	3.905E-16	3.904E-16	3.903E-16	3.904E-16	3.921E-16	1.872E-16	3.242E-16	37.24
30 000	3.771E-16	1.859E-16	3.801E-16	3.771E-16	3.771E-16	1.854E-16	0.000E+00	3.771E-16	3.771E-16	3.772E-16	3.771E-16	3.770E-16	3.771E-16	3.788E-16	1.844E-16	3.139E-16	36.94
40 000	3.519E-16	1.804E-16	3.546E-16	3.519E-16	3.519E-16	1.799E-16	0.000E+00	3.519E-16	3.518E-16	3.519E-16	3.519E-16	3.518E-16	3.519E-16	3.550E-16	1.789E-16	2.944E-16	36.35
45 000	3.399E-16	1.777E-16	3.425E-16	3.399E-16	3.399E-16	1.772E-16	0.000E+00	3.399E-16	3.399E-16	3.400E-16	3.399E-16	3.398E-16	3.399E-16	3.414E-16	1.763E-16	2.849E-16	36.05
50 000	3.283E-16	1.750E-16	3.309E-16	3.283E-16	3.283E-16	1.745E-16	0.000E+00	3.283E-16	3.283E-16	3.284E-16	3.283E-16	3.282E-16	3.283E-16	3.298E-16	1.736E-16	2.759E-16	35.75
100 000	2.321E-16	1.505E-16	2.340E-16	2.321E-16	2.321E-16	1.501E-16	0.000E+00	2.321E-16	2.321E-16	2.323E-16	2.321E-16	2.321E-16	2.321E-16	2.426E-16	1.493E-16	2.010E-16	32.90
500 000	1.450E-17	4.508E-17	1.463E-17	1.451E-17	1.451E-17	4.497E-17	1.451E-17	1.451E-17	1.451E-17	1.454E-17	1.450E-17	1.450E-17	1.450E-17	2.098E-17	4.474E-17	2.103E-17	52.38
1 000 000	4.531E-19	9.989E-18	4.572E-19	4.531E-19	4.534E-19	9.965E-18	4.535E-19	4.535E-19	4.537E-19	4.555E-19	4.531E-19	4.530E-19	4.531E-19	7.245E-19	9.915E-18	2.372E-18	145.46

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.15. Time-dependent ^{126}Sb atom densities

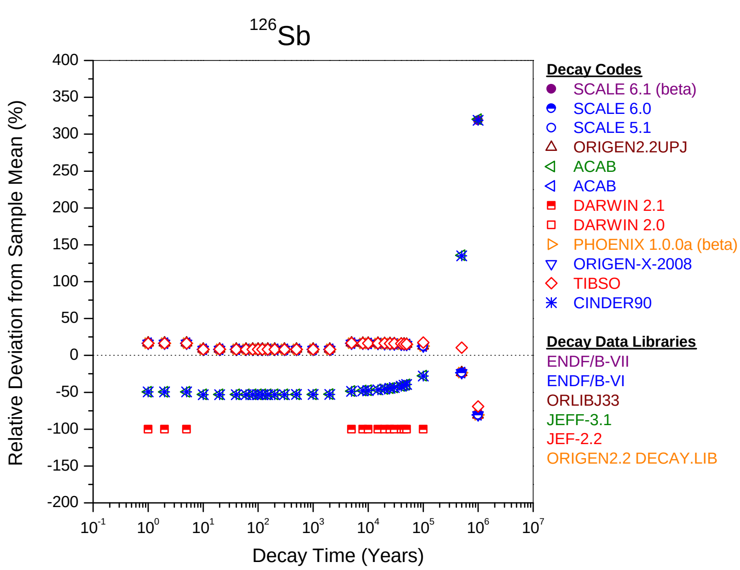
^{126}Sb is a fission product nuclide important for radiological dose assessments. This nuclide, which has a half-life of 12.35 ± 0.06 days and decays by beta-particle emission [20], is formed as a result of the ^{126}Sn(β^-)^{126m}Sb(IT)^{126}Sb decay chain. The ^{126}Sb half-life values and the uncertainty associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 31. ^{126m}Sb branching fraction for isomeric transition is 0.14 in all the evaluated decay libraries [12–15, 20 and 21]; the ^{126}Sn half-life values associated with those libraries are provided in Section 3.13. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 32. In the table, the calculated ^{126}Sb atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{126}Sb using the evaluated decay codes/data libraries is illustrated in Figure 17. The significant dispersion of the calculation results observed at long decay times (e.g. RSD ≈ 145% at 10^6 years) is consistent with the variability of the ^{126}Sn half-life values.

Table 31. ^{126}Sb half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	1.06704E+06	1.07136E+06	1.07136E+06	1.07136E+06	1.07700E+06	1.07100E+06
Uncertainty (s)	5.18400E+03	8.64000E+03	8.64000E+03	-	3.00000E+03	-

Sources: References 12, 13, 15, 20 and 21.

Figure 17. Relative difference from sample mean as a function of decay time for ^{126}Sb atom density



Note: For a decay code using multiple sources of decay data, only the primary decay data source is indicated in the figure.

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Table 32. Decay calculation results for ^{126}Sb (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.384E-10	2.383E-10	2.383E-10	0.00
1	6.107E-14	2.646E-14	6.140E-14	6.109E-14	6.106E-14	2.655E-14	0.000E+00	6.109E-14	6.106E-14	6.109E-14	6.107E-14	6.107E-14	6.109E-14	6.098E-14	2.645E-14	5.010E-14	38.80
2	6.108E-14	2.645E-14	6.140E-14	6.109E-14	6.106E-14	2.655E-14	0.000E+00	6.109E-14	6.106E-14	6.108E-14	6.107E-14	6.107E-14	6.108E-14	6.097E-14	2.645E-14	5.010E-14	38.81
5	6.108E-14	2.645E-14	6.140E-14	6.109E-14	6.106E-14	2.655E-14	0.000E+00	6.109E-14	6.106E-14	6.108E-14	6.108E-14	6.107E-14	6.108E-14	6.097E-14	2.645E-14	5.010E-14	38.81
10	6.108E-14	2.645E-14	6.140E-14	6.108E-14	6.106E-14	2.655E-14	6.108E-14	6.108E-14	6.106E-14	6.108E-14	6.108E-14	6.106E-14	6.108E-14	6.097E-14	2.645E-14	5.417E-14	23.19
20	6.108E-14	2.645E-14	6.139E-14	6.108E-14	6.106E-14	2.655E-14	6.108E-14	6.108E-14	6.105E-14	6.108E-14	6.108E-14	6.106E-14	6.108E-14	6.118E-14	2.645E-14	5.418E-14	23.20
40	6.107E-14	2.645E-14	6.138E-14	6.107E-14	6.105E-14	2.655E-14	6.107E-14	6.107E-14	6.104E-14	6.107E-14	6.107E-14	6.105E-14	6.107E-14	6.107E-14	2.645E-14	5.417E-14	23.19
60	6.106E-14	2.645E-14	6.138E-14	6.106E-14	6.104E-14	2.655E-14	6.106E-14	6.106E-14	6.103E-14	6.106E-14	6.106E-14	6.104E-14	6.106E-14	6.106E-14	2.645E-14	5.416E-14	23.19
80	6.105E-14	2.645E-14	6.137E-14	6.105E-14	6.103E-14	2.654E-14	6.105E-14	6.105E-14	6.103E-14	6.105E-14	6.105E-14	6.103E-14	6.105E-14	6.105E-14	2.644E-14	5.415E-14	23.19
100	6.104E-14	2.644E-14	6.136E-14	6.105E-14	6.102E-14	2.654E-14	6.104E-14	6.104E-14	6.102E-14	6.104E-14	6.104E-14	6.103E-14	6.104E-14	6.104E-14	2.644E-14	5.415E-14	23.19
120	6.103E-14	2.644E-14	6.135E-14	6.104E-14	6.101E-14	2.654E-14	6.104E-14	6.104E-14	6.101E-14	6.103E-14	6.103E-14	6.102E-14	6.103E-14	6.103E-14	2.644E-14	5.414E-14	23.18
150	6.102E-14	2.644E-14	6.134E-14	6.103E-14	6.100E-14	2.654E-14	6.102E-14	6.102E-14	6.100E-14	6.102E-14	6.102E-14	6.101E-14	6.102E-14	6.106E-14	2.644E-14	5.413E-14	23.18
200	6.100E-14	2.644E-14	6.132E-14	6.100E-14	6.098E-14	2.653E-14	6.100E-14	6.100E-14	6.098E-14	6.100E-14	6.100E-14	6.098E-14	6.100E-14	6.102E-14	2.643E-14	5.411E-14	23.18
300	6.096E-14	2.643E-14	6.127E-14	6.096E-14	6.094E-14	2.653E-14	6.096E-14	6.096E-14	6.093E-14	6.096E-14	6.096E-14	6.094E-14	6.096E-14	6.096E-14	2.643E-14	5.408E-14	23.17
500	6.087E-14	2.641E-14	6.119E-14	6.088E-14	6.085E-14	2.651E-14	6.088E-14	6.088E-14	6.085E-14	6.087E-14	6.087E-14	6.086E-14	6.087E-14	6.089E-14	2.641E-14	5.401E-14	23.16
1 000	6.066E-14	2.637E-14	6.098E-14	6.067E-14	6.064E-14	2.647E-14	6.067E-14	6.067E-14	6.064E-14	6.066E-14	6.066E-14	6.065E-14	6.066E-14	6.069E-14	2.637E-14	5.383E-14	23.12
2 000	6.024E-14	2.629E-14	6.056E-14	6.025E-14	6.022E-14	2.639E-14	6.025E-14	6.025E-14	6.022E-14	6.025E-14	6.024E-14	6.023E-14	6.024E-14	6.030E-14	2.629E-14	5.348E-14	23.04
5 000	5.900E-14	2.606E-14	5.931E-14	5.901E-14	5.898E-14	2.615E-14	0.000E+00	5.901E-14	5.898E-14	5.901E-14	5.900E-14	5.899E-14	5.900E-14	5.916E-14	2.605E-14	4.851E-14	38.52
8 000	5.779E-14	2.582E-14	5.809E-14	5.779E-14	5.777E-14	2.592E-14	0.000E+00	5.779E-14	5.777E-14	5.779E-14	5.779E-14	5.777E-14	5.779E-14	5.794E-14	2.582E-14	4.758E-14	38.35
10 000	5.699E-14	2.567E-14	5.729E-14	5.700E-14	5.698E-14	2.576E-14	0.000E+00	5.700E-14	5.697E-14	5.700E-14	5.699E-14	5.698E-14	5.699E-14	5.710E-14	2.566E-14	4.696E-14	38.23
15 000	5.505E-14	2.528E-14	5.534E-14	5.506E-14	5.503E-14	2.538E-14	0.000E+00	5.505E-14	5.503E-14	5.506E-14	5.505E-14	5.504E-14	5.505E-14	5.530E-14	2.528E-14	4.547E-14	37.95
20 000	5.318E-14	2.490E-14	5.345E-14	5.318E-14	5.316E-14	2.500E-14	0.000E+00	5.318E-14	5.316E-14	5.318E-14	5.318E-14	5.316E-14	5.318E-14	5.342E-14	2.490E-14	4.401E-14	37.65
25 000	5.136E-14	2.453E-14	5.163E-14	5.137E-14	5.135E-14	2.462E-14	0.000E+00	5.137E-14	5.135E-14	5.137E-14	5.137E-14	5.135E-14	5.137E-14	5.160E-14	2.453E-14	4.261E-14	37.36
30 000	4.961E-14	2.416E-14	4.987E-14	4.962E-14	4.960E-14	2.426E-14	0.000E+00	4.962E-14	4.960E-14	4.962E-14	4.962E-14	4.960E-14	4.962E-14	4.984E-14	2.416E-14	4.125E-14	37.06
40 000	4.629E-14	2.345E-14	4.653E-14	4.630E-14	4.628E-14	2.354E-14	0.000E+00	4.630E-14	4.628E-14	4.630E-14	4.629E-14	4.628E-14	4.629E-14	4.671E-14	2.345E-14	3.869E-14	36.47
45 000	4.472E-14	2.310E-14	4.495E-14	4.472E-14	4.470E-14	2.318E-14	0.000E+00	4.472E-14	4.470E-14	4.473E-14	4.472E-14	4.470E-14	4.472E-14	4.492E-14	2.310E-14	3.744E-14	36.17
50 000	4.319E-14	2.275E-14	4.342E-14	4.319E-14	4.318E-14	2.284E-14	0.000E+00	4.320E-14	4.318E-14	4.320E-14	4.319E-14	4.318E-14	4.319E-14	4.339E-14	2.275E-14	3.626E-14	35.87
100 000	3.054E-14	1.957E-14	3.070E-14	3.054E-14	3.053E-14	1.964E-14	0.000E+00	3.054E-14	3.053E-14	3.056E-14	3.054E-14	3.053E-14	3.054E-14	3.192E-14	1.957E-14	2.642E-14	33.02
500 000	1.908E-15	5.861E-15	1.919E-15	1.908E-15	1.908E-15	5.884E-15	1.909E-15	1.909E-15	1.909E-15	1.913E-15	1.908E-15	1.908E-15	1.908E-15	2.760E-15	5.862E-15	2.758E-15	51.88
1 000 000	5.961E-17	1.299E-15	5.999E-17	5.962E-17	5.963E-17	1.304E-15	5.966E-17	5.966E-17	5.967E-17	5.993E-17	5.961E-17	5.960E-17	5.961E-17	9.533E-17	1.299E-15	3.103E-16	145.02

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.16. Time-dependent ^{129}I atom densities

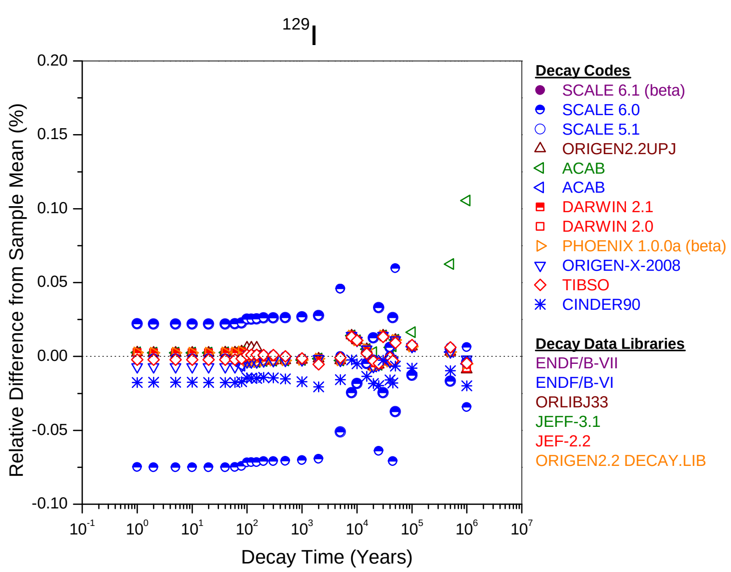
^{129}I is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of $1.57 \times 10^7 \pm 4 \times 10^5$ years and decays by beta-particle emission [20]. A very small fraction of ^{129}I is formed as a result of complete decay of ^{129m}Te ($T_{1/2}$ = 33.6 days) within a year from fuel discharge. The ^{129}I half-life values and the uncertainty associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 33. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 34. In the table, the calculated ^{129}I atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{129}I using the evaluated decay codes/data libraries is illustrated in Figure 18. The ^{129}I atom density results at any given decay time are practically identical.

Table 33. ^{129}I half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	4.95454E+14	4.95444E+14	5.08067E+14	4.95453E+14	4.95000E+14	4.95400E+14
Uncertainty (s)	1.26230E+13	1.26228E+13	2.20898E+13	-	1.30000E+13	-

Sources: References 12, 13, 15, 20 and 21.

Figure 18. Relative difference from sample mean as a function of decay time for ^{129}I atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 34. Decay calculation results for ^{129}I (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	1.025E-05	0.00
1	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
2	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
5	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
10	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
20	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
40	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
60	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
80	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
100	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
120	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
150	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
200	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
300	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
500	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
1 000	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
2 000	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	0.02
5 000	1.031E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	1.032E-05	1.031E-05	1.032E-05	0.03
8 000	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	0.02
10 000	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	0.01
15 000	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	0.00
20 000	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	0.01
25 000	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.031E-05	1.030E-05	1.031E-05	1.031E-05	1.030E-05	1.031E-05	0.03
30 000	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	0.02
40 000	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	0.00
45 000	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.029E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	0.02
50 000	1.029E-05	1.029E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.030E-05	1.029E-05	1.029E-05	1.029E-05	1.029E-05	1.029E-05	1.029E-05	0.03
100 000	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	1.027E-05	0.01
500 000	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.010E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	1.009E-05	0.02
1 000 000	9.872E-06	9.872E-06	9.872E-06	9.873E-06	9.872E-06	9.883E-06	9.872E-06	9.872E-06	9.872E-06	9.872E-06	9.872E-06	9.869E-06	9.872E-06	9.872E-06	9.870E-06	9.872E-06	0.03

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.17. Time-dependent ^{135}Cs atom densities

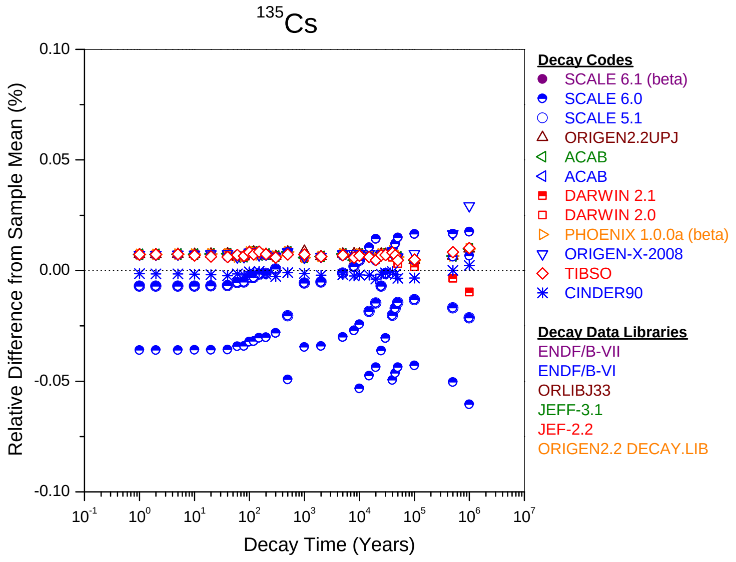
^{135}Cs is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of $2.3\times10^6 \pm 3\times10^5$ years and decays by beta-particle emission [20]. A very small fraction of ^{135}Cs is formed due to ^{135}I ($T_{1/2}$ = 6.57 hours) and ^{135}Xe ($T_{1/2}$ = 9.14 hours) decay after fuel discharge. The ^{135}Cs half-life values and the uncertainty associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 35. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 36. In the table, the calculated ^{135}Cs atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{135}Cs using the evaluated decay codes/data libraries is illustrated in Figure 19. The ^{135}Cs results at any given decay time are practically identical.

Table 35. ^{135}Cs half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	7.25824E+13	7.25809E+13	7.25809E+13	7.25824E+13	7.25824E+13	7.25800E+13
Uncertainty (s)	9.46728E+12	9.46708E+12	9.46708E+12	-	9.46728E+12	-

Sources: References 12–14, 20 and 21.

Figure 19. Relative difference from sample mean as a function of decay time for ^{135}Cs atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 36. Decay calculation results for ^{135}Cs (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	0.00
1	3.465E-05	3.465E-05	3.466E-05	3.464E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.465E-05	3.465E-05	3.465E-05	3.466E-05	3.465E-05	3.465E-05	0.01
2	3.465E-05	3.465E-05	3.466E-05	3.464E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.465E-05	3.465E-05	3.465E-05	3.466E-05	3.465E-05	3.465E-05	0.01
5	3.465E-05	3.465E-05	3.466E-05	3.464E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.465E-05	3.465E-05	3.465E-05	3.466E-05	3.465E-05	3.465E-05	0.01
10	3.465E-05	3.465E-05	3.466E-05	3.464E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
20	3.465E-05	3.465E-05	3.466E-05	3.464E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
40	3.465E-05	3.465E-05	3.466E-05	3.464E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.466E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
60	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
80	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
100	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
120	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
150	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
200	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
300	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.01
500	3.464E-05	3.465E-05	3.465E-05	3.463E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	3.464E-05	3.465E-05	3.465E-05	3.465E-05	3.465E-05	0.02
1 000	3.464E-05	3.464E-05	3.465E-05	3.463E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	3.464E-05	0.01
2 000	3.463E-05	3.463E-05	3.463E-05	3.462E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	3.463E-05	0.01
5 000	3.460E-05	3.460E-05	3.460E-05	3.459E-05	3.460E-05	3.460E-05	3.460E-05	3.460E-05	3.460E-05	3.460E-05	3.460E-05	3.459E-05	3.460E-05	3.460E-05	3.460E-05	3.460E-05	0.01
8 000	3.457E-05	3.457E-05	3.457E-05	3.456E-05	3.457E-05	3.457E-05	3.457E-05	3.457E-05	3.457E-05	3.457E-05	3.457E-05	3.456E-05	3.457E-05	3.457E-05	3.457E-05	3.457E-05	0.01
10 000	3.455E-05	3.455E-05	3.455E-05	3.453E-05	3.455E-05	3.455E-05	3.455E-05	3.455E-05	3.455E-05	3.455E-05	3.455E-05	3.454E-05	3.455E-05	3.455E-05	3.455E-05	3.455E-05	0.02
15 000	3.449E-05	3.450E-05	3.450E-05	3.448E-05	3.450E-05	3.450E-05	3.450E-05	3.450E-05	3.450E-05	3.450E-05	3.450E-05	3.449E-05	3.450E-05	3.450E-05	3.450E-05	3.450E-05	0.02
20 000	3.444E-05	3.445E-05	3.445E-05	3.443E-05	3.445E-05	3.445E-05	3.445E-05	3.445E-05	3.445E-05	3.445E-05	3.445E-05	3.444E-05	3.445E-05	3.445E-05	3.444E-05	3.445E-05	0.02
25 000	3.439E-05	3.439E-05	3.440E-05	3.438E-05	3.440E-05	3.440E-05	3.440E-05	3.440E-05	3.440E-05	3.440E-05	3.439E-05	3.439E-05	3.439E-05	3.439E-05	3.439E-05	3.439E-05	0.01
30 000	3.434E-05	3.434E-05	3.434E-05	3.433E-05	3.434E-05	3.434E-05	3.434E-05	3.434E-05	3.434E-05	3.434E-05	3.434E-05	3.433E-05	3.434E-05	3.434E-05	3.434E-05	3.434E-05	0.01
40 000	3.423E-05	3.424E-05	3.424E-05	3.422E-05	3.424E-05	3.424E-05	3.424E-05	3.424E-05	3.424E-05	3.424E-05	3.424E-05	3.423E-05	3.424E-05	3.424E-05	3.424E-05	3.424E-05	0.02
45 000	3.418E-05	3.419E-05	3.419E-05	3.417E-05	3.419E-05	3.419E-05	3.419E-05	3.419E-05	3.419E-05	3.419E-05	3.419E-05	3.418E-05	3.419E-05	3.419E-05	3.419E-05	3.419E-05	0.02
50 000	3.413E-05	3.414E-05	3.414E-05	3.412E-05	3.414E-05	3.414E-05	3.414E-05	3.414E-05	3.414E-05	3.414E-05	3.414E-05	3.413E-05	3.414E-05	3.414E-05	3.413E-05	3.413E-05	0.02
100 000	3.362E-05	3.363E-05	3.363E-05	3.361E-05	3.363E-05	3.363E-05	3.363E-05	3.363E-05	3.363E-05	3.363E-05	3.363E-05	3.362E-05	3.363E-05	3.363E-05	3.362E-05	3.362E-05	0.02
500 000	2.980E-05	2.981E-05	2.981E-05	2.979E-05	2.981E-05	2.981E-05	2.980E-05	2.980E-05	2.981E-05	2.981E-05	2.981E-05	2.980E-05	2.981E-05	2.981E-05	2.981E-05	2.981E-05	0.02
1 000 000	2.563E-05	2.564E-05	2.564E-05	2.562E-05	2.564E-05	2.564E-05	2.563E-05	2.563E-05	2.564E-05	2.564E-05	2.564E-05	2.563E-05	2.564E-05	2.564E-05	2.564E-05	2.564E-05	0.02

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.18. Time-dependent ^{137}Cs atom densities

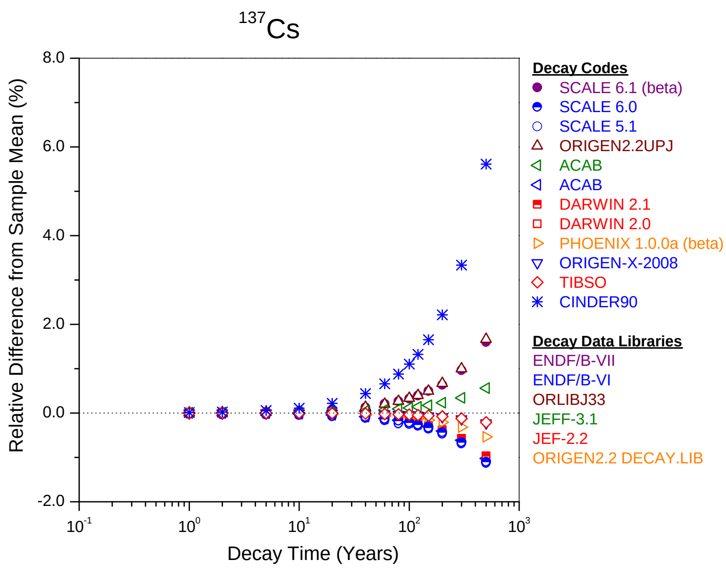
^{137}Cs is a fission product nuclide important for radiological dose assessments. This nuclide has a half-life of 30.07 ± 0.03 years and decays by beta-particle emission [20]. The ^{137}Cs half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 37. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 38. In the table, the calculated ^{137}Cs atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{137}Cs using the evaluated decay codes/data libraries is illustrated in Figure 20. A very small dispersion (RSD ≈ 1%) of the decay calculation results is observed at 500 years after fuel discharge.

Table 37. ^{137}Cs half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	9.48937E+08	9.46708E+08	9.47990E+08	9.46708E+08	9.48900+08	9.46700E+08
Uncertainty (s)	9.46728E+05	6.31139E+06	9.46728E+05	-	1.00000E+06	-

Sources: References 12, 13, 15, 20 and 21.

Figure 20. Relative difference from sample mean as a function of decay time for ^{137}Cs atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 38. Decay calculation results for ^{137}Cs (atom/barn·cm)

Decay time (year)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	7.511E-05	0.00
1	7.339E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.340E-05	7.338E-05	7.340E-05	7.340E-05	7.341E-05	7.340E-05	0.01
2	7.172E-05	7.173E-05	7.173E-05	7.173E-05	7.172E-05	7.173E-05	7.172E-05	7.172E-05	7.172E-05	7.172E-05	7.172E-05	7.170E-05	7.172E-05	7.172E-05	7.174E-05	7.172E-05	0.01
5	6.691E-05	6.694E-05	6.694E-05	6.692E-05	6.692E-05	6.693E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.692E-05	6.690E-05	6.692E-05	6.692E-05	6.696E-05	6.692E-05	0.01
10	5.961E-05	5.965E-05	5.965E-05	5.962E-05	5.962E-05	5.964E-05	5.962E-05	5.962E-05	5.962E-05	5.963E-05	5.962E-05	5.960E-05	5.962E-05	5.963E-05	5.969E-05	5.963E-05	0.02
20	4.731E-05	4.737E-05	4.737E-05	4.732E-05	4.732E-05	4.735E-05	4.732E-05	4.732E-05	4.733E-05	4.733E-05	4.732E-05	4.730E-05	4.732E-05	4.733E-05	4.744E-05	4.734E-05	0.04
40	2.980E-05	2.987E-05	2.987E-05	2.981E-05	2.981E-05	2.985E-05	2.981E-05	2.981E-05	2.982E-05	2.983E-05	2.981E-05	2.980E-05	2.981E-05	2.983E-05	2.996E-05	2.983E-05	0.08
60	1.877E-05	1.884E-05	1.884E-05	1.878E-05	1.878E-05	1.881E-05	1.878E-05	1.878E-05	1.879E-05	1.880E-05	1.878E-05	1.877E-05	1.878E-05	1.880E-05	1.892E-05	1.880E-05	0.12
80	1.183E-05	1.188E-05	1.188E-05	1.183E-05	1.183E-05	1.186E-05	1.183E-05	1.183E-05	1.184E-05	1.184E-05	1.183E-05	1.182E-05	1.183E-05	1.184E-05	1.195E-05	1.185E-05	0.16
100	7.450E-06	7.491E-06	7.492E-06	7.451E-06	7.452E-06	7.475E-06	7.453E-06	7.453E-06	7.459E-06	7.464E-06	7.451E-06	7.448E-06	7.451E-06	7.464E-06	7.549E-06	7.467E-06	0.20
120	4.693E-06	4.724E-06	4.725E-06	4.694E-06	4.694E-06	4.712E-06	4.695E-06	4.695E-06	4.700E-06	4.703E-06	4.693E-06	4.692E-06	4.693E-06	4.703E-06	4.768E-06	4.706E-06	0.24
150	2.346E-06	2.366E-06	2.366E-06	2.347E-06	2.347E-06	2.358E-06	2.348E-06	2.348E-06	2.351E-06	2.353E-06	2.347E-06	2.346E-06	2.347E-06	2.353E-06	2.393E-06	2.354E-06	0.30
200	7.390E-07	7.470E-07	7.472E-07	7.391E-07	7.393E-07	7.440E-07	7.394E-07	7.394E-07	7.407E-07	7.416E-07	7.390E-07	7.388E-07	7.390E-07	7.417E-07	7.587E-07	7.423E-07	0.40
300	7.330E-08	7.450E-08	7.453E-08	7.331E-08	7.334E-08	7.404E-08	7.336E-08	7.336E-08	7.355E-08	7.369E-08	7.330E-08	7.328E-08	7.330E-08	7.370E-08	7.625E-08	7.379E-08	0.60
500	7.212E-10	7.409E-10	7.414E-10	7.213E-10	7.218E-10	7.333E-10	7.222E-10	7.222E-10	7.253E-10	7.276E-10	7.212E-10	7.210E-10	7.212E-10	7.277E-10	7.702E-10	7.292E-10	0.99

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.19. Time-dependent ^{147}Sm atom densities

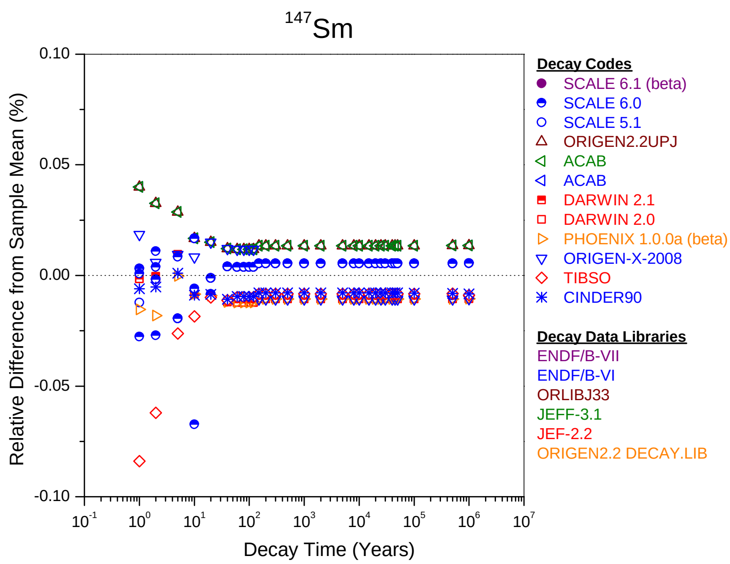
^{147}Sm is a stable fission product nuclide important for burn-up credit criticality safety analyses. Approximately 60% of the ^{147}Sm concentration at decay times greater than 10 years is the result of ^{147}Pm ($T_{1/2}$ = 2.6234 ± 0.0002 years) beta decay. The ^{147}Pm half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 39. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 40. In the table, the calculated ^{147}Sm atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{147}Sm using the evaluated decay codes/data libraries illustrated in Figure 21 indicates negligible differences among the calculated ^{147}Sm atom density values.

Table 39. ^{147}Pm half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	8.27882E+07	8.27864E+07	8.27864E+07	8.26808E+07	8.27864E+07	8.27900E+07
Uncertainty (s)	6.31152E+03	6.31139E+03	6.31139E+03	-	6.31139E+03	-

Sources: References 12, 13, 15, 20 and 21.

Figure 21. Relative difference from sample mean as a function of decay time for ^{147}Sm atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 40. Decay calculation results for ^{147}Sm (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	4.709E-06	0.00
1	6.503E-06	6.504E-06	6.506E-06	6.504E-06	6.506E-06	6.506E-06	6.504E-06	6.504E-06	6.503E-06	6.505E-06	6.504E-06	6.502E-06	6.504E-06	6.498E-06	6.503E-06	6.504E-06	0.03
2	7.884E-06	7.884E-06	7.887E-06	7.885E-06	7.887E-06	7.887E-06	7.884E-06	7.884E-06	7.883E-06	7.885E-06	7.884E-06	7.882E-06	7.884E-06	7.879E-06	7.884E-06	7.884E-06	0.02
5	1.038E-05	1.038E-05	1.039E-05	1.038E-05	1.039E-05	1.039E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	1.038E-05	0.02
10	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	1.189E-05	1.190E-05	1.190E-05	1.190E-05	1.190E-05	0.02
20	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	1.241E-05	0.01
40	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
60	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
80	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
100	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
120	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
150	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
200	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
300	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
500	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
1 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
2 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
5 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
8 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
10 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
15 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
20 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
25 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
30 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
40 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
45 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
50 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
100 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
500 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01
1 000 000	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	1.245E-05	0.01

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.20. Time-dependent ^{151}Sm atom densities

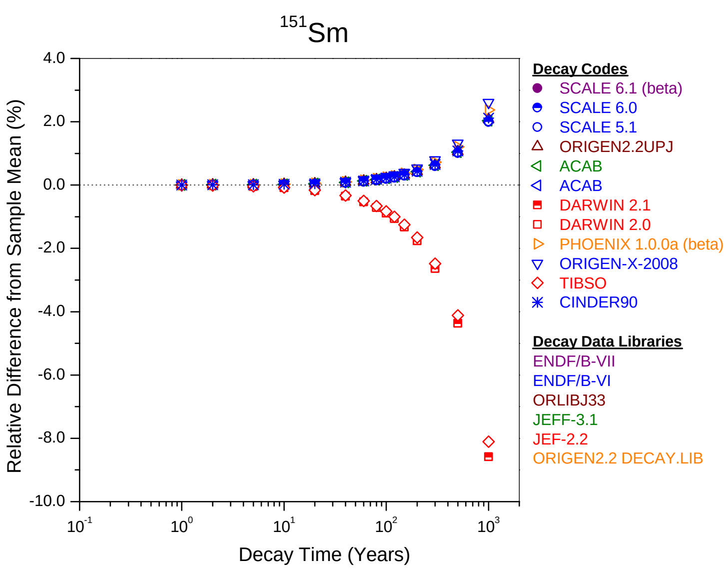
^{151}Sm is a fission product nuclide important for burn-up credit criticality safety analyses. This nuclide has a half-life of 90 ± 8 years and decays by beta-particle emission [20]. Approximately 1% of the time-dependent ^{151}Sm concentrations is produced as a results of ^{151}Pm ($T_{1/2}$ = 28.4 ± 0.4 hours) beta decay a short time after fuel discharge. The ^{151}Sm half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 41. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 42. In the table, the calculated ^{151}Sm atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{151}Sm using the evaluated decay codes/data libraries is illustrated in Figure 22. As seen in the figure, the ^{151}Sm atom density values based on the JEF-2.2 decay data are slightly lower at very long decay times than the values calculated using the other decay data libraries (e.g. ~ 12% lower at 10^3 years), consistently with the ^{151}Sm half-life values used.

Table 41. ^{151}Sm half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	2.84018E+09	2.84012E+09	2.84018E+09	2.80005E+09	2.84018E+09	2.84000E+09
Uncertainty (s)	2.52461E+08	1.89342E+08	1.89346E+08	-	2.52461E+08	-

Sources: References 12, 13, 15, 20 and 21.

Figure 22. Relative difference from sample mean as a function of decay time for ^{151}Sm atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 42. Decay calculation results for ^{151}Sm (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	9.711E-07	0.00
1	9.721E-07	9.722E-07	9.722E-07	9.723E-07	9.722E-07	9.722E-07	9.721E-07	9.721E-07	9.722E-07	9.722E-07	9.722E-07	9.720E-07	9.722E-07	9.721E-07	9.722E-07	9.722E-07	0.01
2	9.646E-07	9.647E-07	9.647E-07	9.648E-07	9.647E-07	9.647E-07	9.645E-07	9.645E-07	9.647E-07	9.647E-07	9.647E-07	9.645E-07	9.647E-07	9.645E-07	9.647E-07	9.647E-07	0.01
5	9.426E-07	9.427E-07	9.427E-07	9.428E-07	9.427E-07	9.427E-07	9.422E-07	9.422E-07	9.427E-07	9.427E-07	9.427E-07	9.425E-07	9.427E-07	9.422E-07	9.427E-07	9.426E-07	0.02
10	9.070E-07	9.071E-07	9.071E-07	9.071E-07	9.071E-07	9.071E-07	9.061E-07	9.061E-07	9.071E-07	9.071E-07	9.071E-07	9.069E-07	9.071E-07	9.061E-07	9.071E-07	9.069E-07	0.04
20	8.397E-07	8.398E-07	8.398E-07	8.399E-07	8.398E-07	8.398E-07	8.380E-07	8.380E-07	8.399E-07	8.399E-07	8.398E-07	8.396E-07	8.398E-07	8.381E-07	8.399E-07	8.395E-07	0.09
40	7.198E-07	7.199E-07	7.200E-07	7.200E-07	7.199E-07	7.199E-07	7.168E-07	7.168E-07	7.200E-07	7.201E-07	7.199E-07	7.198E-07	7.199E-07	7.169E-07	7.200E-07	7.193E-07	0.18
60	6.171E-07	6.172E-07	6.172E-07	6.172E-07	6.172E-07	6.172E-07	6.131E-07	6.131E-07	6.173E-07	6.174E-07	6.171E-07	6.170E-07	6.171E-07	6.133E-07	6.172E-07	6.164E-07	0.27
80	5.290E-07	5.290E-07	5.291E-07	5.291E-07	5.291E-07	5.291E-07	5.244E-07	5.244E-07	5.292E-07	5.293E-07	5.290E-07	5.289E-07	5.290E-07	5.246E-07	5.291E-07	5.282E-07	0.36
100	4.535E-07	4.535E-07	4.535E-07	4.535E-07	4.535E-07	4.535E-07	4.486E-07	4.486E-07	4.537E-07	4.538E-07	4.535E-07	4.534E-07	4.535E-07	4.488E-07	4.536E-07	4.526E-07	0.45
120	3.887E-07	3.888E-07	3.888E-07	3.888E-07	3.888E-07	3.888E-07	3.837E-07	3.837E-07	3.889E-07	3.890E-07	3.888E-07	3.887E-07	3.888E-07	3.839E-07	3.888E-07	3.878E-07	0.54
150	3.085E-07	3.086E-07	3.086E-07	3.086E-07	3.086E-07	3.086E-07	3.035E-07	3.035E-07	3.087E-07	3.088E-07	3.086E-07	3.085E-07	3.086E-07	3.038E-07	3.086E-07	3.076E-07	0.67
200	2.099E-07	2.099E-07	2.100E-07	2.099E-07	2.099E-07	2.099E-07	2.054E-07	2.054E-07	2.101E-07	2.102E-07	2.099E-07	2.099E-07	2.099E-07	2.056E-07	2.100E-07	2.091E-07	0.89
300	9.717E-08	9.718E-08	9.720E-08	9.718E-08	9.719E-08	9.719E-08	9.403E-08	9.403E-08	9.728E-08	9.735E-08	9.718E-08	9.715E-08	9.718E-08	9.418E-08	9.721E-08	9.658E-08	1.34
500	2.082E-08	2.082E-08	2.083E-08	2.082E-08	2.083E-08	2.083E-08	1.971E-08	1.971E-08	2.086E-08	2.088E-08	2.082E-08	2.082E-08	2.082E-08	1.976E-08	2.083E-08	2.061E-08	2.22
1 000	4.425E-10	4.426E-10	4.429E-10	4.426E-10	4.427E-10	4.427E-10	3.966E-10	3.966E-10	4.442E-10	4.452E-10	4.426E-10	4.425E-10	4.426E-10	3.987E-10	4.430E-10	4.339E-10	4.36

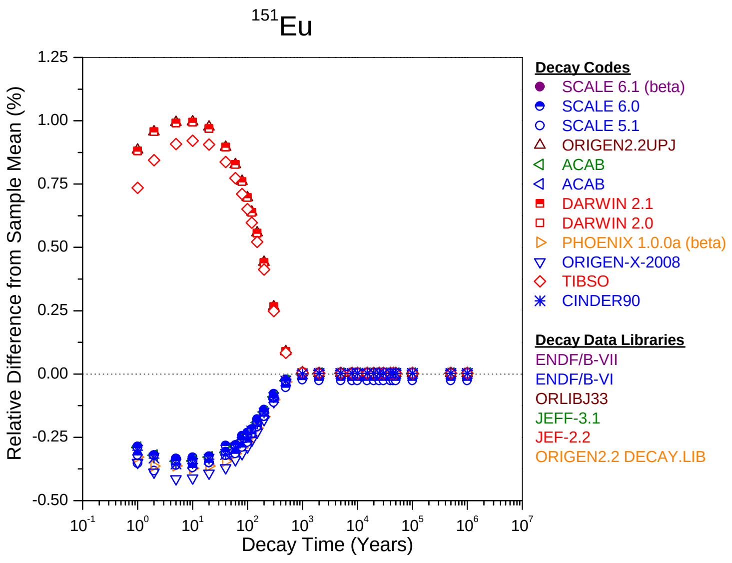
[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.21. Time-dependent ^{151}Eu atom densities

^{151}Eu is a stable fission product nuclide important for burn-up credit criticality safety analyses. However, ^{151}Eu concentrations increase after fuel discharge and reach a stable value at approximately 10^3 years as a result of ^{151}Sm beta decay ($T_{1/2}$ = 90 ± 8 years). The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 43. In the table, the calculated ^{151}Eu atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{151}Eu using the evaluated decay codes/data libraries is illustrated in Figure 23. A very small dispersion of the decay calculation results for ^{151}Eu is observed for the first 10^3 years after fuel discharge (RSD < 0.6%), which is consistent with the different ^{151}Sm half-life values used.

Figure 23. Relative difference from sample mean as a function of decay time for ^{151}Eu atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 43. Decay calculation results for ^{151}Eu (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	1.564E-09	0.00
1	9.075E-09	9.081E-09	9.188E-09	9.081E-09	9.081E-09	9.081E-09	9.187E-09	9.187E-09	9.077E-09	9.075E-09	9.081E-09	9.078E-09	9.081E-09	9.174E-09	9.080E-09	9.107E-09	0.53
2	1.653E-08	1.654E-08	1.675E-08	1.654E-08	1.654E-08	1.654E-08	1.675E-08	1.675E-08	1.653E-08	1.653E-08	1.654E-08	1.654E-08	1.654E-08	1.673E-08	1.654E-08	1.659E-08	0.58
5	3.857E-08	3.858E-08	3.909E-08	3.858E-08	3.858E-08	3.858E-08	3.909E-08	3.909E-08	3.857E-08	3.855E-08	3.858E-08	3.857E-08	3.858E-08	3.906E-08	3.857E-08	3.871E-08	0.61
10	7.418E-08	7.419E-08	7.519E-08	7.420E-08	7.419E-08	7.419E-08	7.519E-08	7.519E-08	7.417E-08	7.414E-08	7.419E-08	7.417E-08	7.419E-08	7.513E-08	7.418E-08	7.445E-08	0.61
20	1.414E-07	1.414E-07	1.433E-07	1.414E-07	1.414E-07	1.414E-07	1.433E-07	1.433E-07	1.414E-07	1.413E-07	1.414E-07	1.414E-07	1.414E-07	1.432E-07	1.414E-07	1.419E-07	0.60
40	2.613E-07	2.613E-07	2.645E-07	2.614E-07	2.613E-07	2.613E-07	2.645E-07	2.645E-07	2.612E-07	2.612E-07	2.613E-07	2.613E-07	2.613E-07	2.643E-07	2.613E-07	2.621E-07	0.55
60	3.641E-07	3.641E-07	3.682E-07	3.641E-07	3.641E-07	3.641E-07	3.682E-07	3.682E-07	3.640E-07	3.639E-07	3.641E-07	3.640E-07	3.641E-07	3.680E-07	3.641E-07	3.651E-07	0.51
80	4.522E-07	4.522E-07	4.569E-07	4.523E-07	4.522E-07	4.522E-07	4.569E-07	4.569E-07	4.521E-07	4.520E-07	4.522E-07	4.521E-07	4.522E-07	4.566E-07	4.522E-07	4.534E-07	0.47
100	5.277E-07	5.278E-07	5.327E-07	5.278E-07	5.278E-07	5.278E-07	5.327E-07	5.327E-07	5.276E-07	5.275E-07	5.278E-07	5.276E-07	5.278E-07	5.325E-07	5.277E-07	5.290E-07	0.43
120	5.924E-07	5.925E-07	5.976E-07	5.925E-07	5.925E-07	5.925E-07	5.976E-07	5.976E-07	5.924E-07	5.922E-07	5.925E-07	5.924E-07	5.925E-07	5.973E-07	5.925E-07	5.938E-07	0.39
150	6.726E-07	6.727E-07	6.778E-07	6.728E-07	6.727E-07	6.727E-07	6.778E-07	6.778E-07	6.726E-07	6.725E-07	6.727E-07	6.726E-07	6.727E-07	6.775E-07	6.727E-07	6.740E-07	0.34
200	7.712E-07	7.713E-07	7.759E-07	7.714E-07	7.713E-07	7.713E-07	7.759E-07	7.759E-07	7.712E-07	7.711E-07	7.713E-07	7.712E-07	7.713E-07	7.757E-07	7.713E-07	7.725E-07	0.27
300	8.840E-07	8.841E-07	8.872E-07	8.842E-07	8.841E-07	8.841E-07	8.872E-07	8.872E-07	8.840E-07	8.839E-07	8.841E-07	8.839E-07	8.841E-07	8.871E-07	8.841E-07	8.849E-07	0.16
500	9.603E-07	9.605E-07	9.616E-07	9.605E-07	9.605E-07	9.605E-07	9.616E-07	9.616E-07	9.604E-07	9.604E-07	9.604E-07	9.602E-07	9.604E-07	9.615E-07	9.604E-07	9.607E-07	0.06
1 000	9.807E-07	9.808E-07	9.809E-07	9.809E-07	9.808E-07	9.808E-07	9.809E-07	9.809E-07	9.808E-07	9.808E-07	9.808E-07	9.806E-07	9.808E-07	9.809E-07	9.808E-07	9.808E-07	0.01
2 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
5 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
8 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
10 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
15 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
20 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
25 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
30 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
40 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
45 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
50 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
100 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
500 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01
1 000 000	9.811E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.813E-07	9.810E-07	9.813E-07	9.813E-07	9.813E-07	9.812E-07	0.01

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.22. Time-dependent ^{155}Gd atom densities

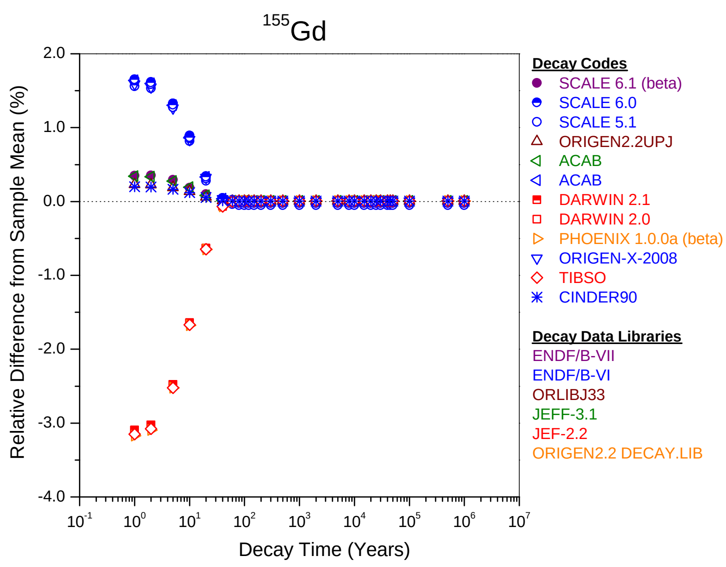
^{155}Gd is a stable fission product nuclide important for burn-up credit criticality safety analyses. However, ^{155}Gd concentrations increase after fuel discharge and reach a stable value at approximately 40 years after fuel discharge as a result of ^{155}Eu beta decay ($T_{1/2}$ = 4.753 ± 0.014 years). The ^{155}Eu half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 44. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 45. In the table, the calculated ^{155}Gd atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{155}Gd using the evaluated decay codes/data libraries is illustrated in Figure 24. A small dispersion of the decay calculation results for ^{155}Gd is observed for the first 40 years after fuel discharge (RSD < 2.1%), which is consistent with the different ^{155}Eu half-life values used.

Table 44. ^{155}Eu half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	1.49993E+08	1.47686E+08	1.49990E+08	1.56522E+08	1.50250E+08	1.56500E+08
Uncertainty (s)	4.41806E+05	1.57785E+06	4.41797E+05	-	5.00000E+04	-

Sources: References 12, 13, 15, 20 and 21.

Figure 24. Relative difference from sample mean as a function of decay time for ^{155}Gd atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 45. Decay calculation results for ^{155}Gd (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	5.462E-09	0.00
1	5.286E-08	5.223E-08	5.217E-08	5.291E-08	5.290E-08	5.223E-08	5.044E-08	5.044E-08	5.040E-08	5.288E-08	5.291E-08	5.290E-08	5.291E-08	5.041E-08	5.215E-08	5.205E-08	2.04
2	9.375E-08	9.266E-08	9.255E-08	9.383E-08	9.381E-08	9.265E-08	8.954E-08	8.954E-08	8.948E-08	9.377E-08	9.382E-08	9.380E-08	9.382E-08	8.949E-08	9.252E-08	9.234E-08	1.99
5	1.857E-07	1.839E-07	1.837E-07	1.858E-07	1.858E-07	1.839E-07	1.788E-07	1.788E-07	1.787E-07	1.857E-07	1.858E-07	1.857E-07	1.858E-07	1.787E-07	1.837E-07	1.834E-07	1.63
10	2.716E-07	2.699E-07	2.698E-07	2.718E-07	2.717E-07	2.699E-07	2.650E-07	2.650E-07	2.649E-07	2.717E-07	2.717E-07	2.717E-07	2.717E-07	2.649E-07	2.697E-07	2.694E-07	1.08
20	3.321E-07	3.315E-07	3.314E-07	3.323E-07	3.323E-07	3.314E-07	3.291E-07	3.291E-07	3.290E-07	3.322E-07	3.323E-07	3.322E-07	3.323E-07	3.290E-07	3.314E-07	3.312E-07	0.41
40	3.490E-07	3.491E-07	3.491E-07	3.492E-07	3.492E-07	3.491E-07	3.488E-07	3.488E-07	3.488E-07	3.492E-07	3.492E-07	3.491E-07	3.492E-07	3.488E-07	3.491E-07	3.490E-07	0.04
60	3.499E-07	3.500E-07	3.500E-07	3.501E-07	3.501E-07	3.500E-07	3.500E-07	3.500E-07	3.500E-07	3.501E-07	3.500E-07	3.500E-07	3.500E-07	3.500E-07	3.500E-07	3.500E-07	0.01
80	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
100	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
120	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
150	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
200	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
300	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
500	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
1 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
2 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
5 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
8 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
10 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
15 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
20 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
25 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
30 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
40 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
45 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
50 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
100 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
500 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02
1 000 000	3.499E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	3.500E-07	3.501E-07	3.501E-07	3.501E-07	3.501E-07	0.02

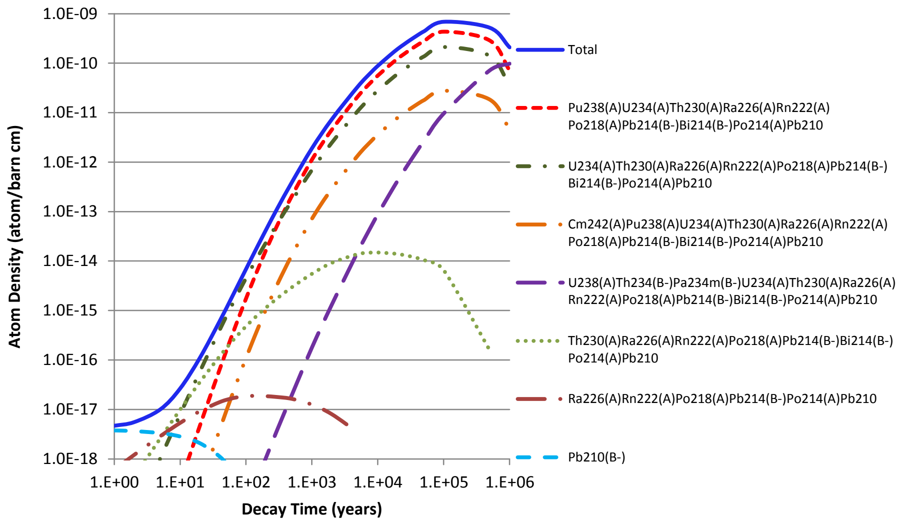
[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.23. Time-dependent ^{210}Pb atom densities

^{210}Pb is a nuclide important for radiological dose assessments. This nuclide has a half-life of 22.20 ± 0.22 years and decays by beta-particle emission [20]. ^{210}Pb concentrations increase after fuel discharge and reach a maximum value at approximately 10^5 years due to a series of decay chains contributing to the formation of the ^{210}Pb nuclide, the most significant being $^{238}Pu(\alpha)^{234}U(\alpha)^{230}Th(\alpha)^{226}Ra(\alpha)^{222}Rn(\alpha)^{218}Po(\alpha)^{214}Pb(\beta^-)^{214}Bi(\beta^-)^{210}Pband^{234}U(\alpha)^{230}Th(\alpha)^{226}Ra(\alpha)^{222}Rn(\alpha)^{218}Po(\alpha)^{214}Pb(\beta^-)^{214}Bi(\beta^-)^{210}Pb$. The cumulative ^{210}Pb atom density and individual contributions from decay chains forming ^{210}Pb are shown as a function of decay time in Figure 25.

Figure 25. ^{210}Pb atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 46. In the table, the calculated ^{210}Pb atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. As seen in the table, the ^{210}Pb atom density values calculated with CINDER 90 decrease with decay time, suggesting that the code may not consider decay chains contributing to the formation of the ^{10}Pb nuclide. A comparison of the results of the decay calculations for ^{210}Pb using decay codes other than CINDER 90 is illustrated in Figure 26. Those results have significant dispersion for decay times greater than 10^3 years (e.g. RSD ≈ 4.3% and 9.7% at 10^3 and 10^6 years, respectively). The ORIGEN-X-2008 result for 2×10^4 years is approximately 10% higher than the other results due to calculation approximations (see Appendix B). TIBSO results significantly differ from the other results for decay times greater than 10^3 years. A review of the decay data for important ^{210}Pb precursors has not identified any differences that would explain the dispersion of the results at decay times greater than 10^3 years. The ^{210}Pb half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 47.

Table 46. Decay calculation results for ^{210}Pb (atom/barn·cm)

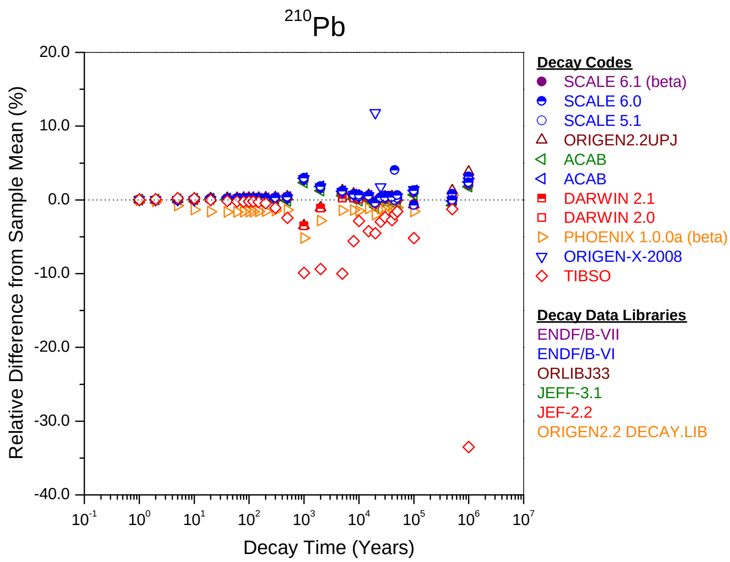
Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean[c]	RSD (%)[c]
0	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	3.886E-18	0.00
1	4.677E-18	4.677E-18	4.677E-18	4.678E-18	4.677E-18	4.677E-18	4.676E-18	4.676E-18	4.673E-18	4.677E-18	4.676E-18	4.676E-18	4.677E-18	4.678E-18	3.767E-18	4.677E-18	0.03
2	5.530E-18	5.530E-18	5.531E-18	5.531E-18	5.530E-18	5.529E-18	5.527E-18	5.527E-18	5.516E-18	5.530E-18	5.529E-18	5.529E-18	5.531E-18	5.533E-18	3.652E-18	5.529E-18	0.07
5	1.002E-17	1.002E-17	1.002E-17	1.002E-17	1.002E-17	1.001E-17	1.001E-17	1.001E-17	9.932E-18	1.001E-17	1.001E-17	1.001E-17	1.002E-17	1.003E-17	3.328E-18	1.001E-17	0.24
10	2.647E-17	2.648E-17	2.648E-17	2.648E-17	2.647E-17	2.646E-17	2.644E-17	2.644E-17	2.609E-17	2.645E-17	2.647E-17	2.647E-17	2.647E-17	2.649E-17	2.852E-18	2.644E-17	0.39
20	1.112E-16	1.113E-16	1.113E-16	1.112E-16	1.112E-16	1.111E-16	1.112E-16	1.112E-16	1.093E-16	1.111E-16	1.112E-16	1.112E-16	1.112E-16	1.110E-16	2.101E-18	1.110E-16	0.47
40	6.158E-16	6.157E-16	6.160E-16	6.158E-16	6.156E-16	6.148E-16	6.155E-16	6.155E-16	6.045E-16	6.148E-16	6.156E-16	6.156E-16	6.158E-16	6.136E-16	1.187E-18	6.146E-16	0.49
60	1.778E-15	1.777E-15	1.778E-15	1.778E-15	1.777E-15	1.774E-15	1.777E-15	1.777E-15	1.745E-15	1.775E-15	1.777E-15	1.777E-15	1.778E-15	1.770E-15	8.472E-19	1.774E-15	0.49
80	3.809E-15	3.806E-15	3.811E-15	3.809E-15	3.808E-15	3.799E-15	3.808E-15	3.808E-15	3.740E-15	3.803E-15	3.808E-15	3.808E-15	3.810E-15	3.792E-15	9.311E-19	3.802E-15	0.48
100	6.885E-15	6.878E-15	6.889E-15	6.885E-15	6.883E-15	6.864E-15	6.884E-15	6.884E-15	6.761E-15	6.874E-15	6.883E-15	6.883E-15	6.886E-15	6.855E-15	1.373E-18	6.871E-15	0.48
120	1.115E-14	1.114E-14	1.116E-14	1.115E-14	1.115E-14	1.111E-14	1.115E-14	1.115E-14	1.095E-14	1.113E-14	1.115E-14	1.115E-14	1.115E-14	1.110E-14	2.151E-18	1.113E-14	0.48
150	2.003E-14	2.000E-14	2.004E-14	2.003E-14	2.003E-14	1.996E-14	2.003E-14	2.003E-14	1.968E-14	2.001E-14	2.003E-14	2.003E-14	2.003E-14	1.994E-14	3.603E-18	1.999E-14	0.48
200	4.221E-14	4.213E-14	4.223E-14	4.221E-14	4.219E-14	4.203E-14	4.221E-14	4.221E-14	4.146E-14	4.216E-14	4.219E-14	4.219E-14	4.221E-14	4.192E-14	6.615E-18	4.211E-14	0.49
300	1.173E-13	1.170E-13	1.174E-13	1.173E-13	1.173E-13	1.167E-13	1.173E-13	1.173E-13	1.152E-13	1.172E-13	1.173E-13	1.173E-13	1.173E-13	1.157E-13	1.358E-17	1.170E-13	0.57
500	3.992E-13	3.981E-13	3.994E-13	3.991E-13	3.990E-13	3.970E-13	3.991E-13	3.991E-13	3.922E-13	3.987E-13	3.990E-13	3.990E-13	3.992E-13	3.878E-13	3.316E-17	3.976E-13	0.85
1 000	1.962E-12	1.955E-12	1.839E-12	1.962E-12	1.961E-12	1.950E-12	1.838E-12	1.838E-12	1.806E-12	1.960E-12	1.961E-12	1.961E-12	1.961E-12	1.717E-12	9.014E-17	1.896E-12	4.27
2 000	7.433E-12	7.409E-12	7.221E-12	7.433E-12	7.431E-12	7.388E-12	7.217E-12	7.217E-12	7.093E-12	7.427E-12	7.430E-12	7.430E-12	7.432E-12	6.615E-12	3.104E-16	7.299E-12	3.12
5 000	3.436E-11	3.425E-11	3.438E-11	3.436E-11	3.435E-11	3.415E-11	3.403E-11	3.403E-11	3.347E-11	3.434E-11	3.435E-11	3.435E-11	3.435E-11	3.056E-11	4.945E-16	3.395E-11	2.97
8 000	6.672E-11	6.650E-11	6.676E-11	6.671E-11	6.670E-11	6.631E-11	6.636E-11	6.636E-11	6.530E-11	6.669E-11	6.669E-11	6.669E-11	6.671E-11	6.250E-11	2.286E-15	6.621E-11	1.71
10 000	8.873E-11	8.844E-11	8.879E-11	8.872E-11	8.871E-11	8.819E-11	8.838E-11	8.838E-11	8.697E-11	8.870E-11	8.869E-11	8.869E-11	8.890E-11	8.577E-11	6.846E-15	8.829E-11	0.98
15 000	1.425E-10	1.420E-10	1.426E-10	1.425E-10	1.424E-10	1.416E-10	1.421E-10	1.421E-10	1.399E-10	1.424E-10	1.424E-10	1.424E-10	1.424E-10	1.356E-10	2.482E-15	1.417E-10	1.31
20 000	1.933E-10	1.927E-10	1.935E-10	1.933E-10	1.933E-10	1.922E-10	1.930E-10	1.930E-10	1.901E-10	2.170E-10	1.933E-10	1.933E-10	1.933E-10	1.852E-10	3.985E-15	1.940E-10	3.58
25 000	2.412E-10	2.404E-10	2.414E-10	2.412E-10	2.412E-10	2.398E-10	2.409E-10	2.409E-10	2.374E-10	2.446E-10	2.411E-10	2.411E-10	2.412E-10	2.333E-10	5.409E-15	2.404E-10	1.05
30 000	2.862E-10	2.853E-10	2.864E-10	2.862E-10	2.862E-10	2.845E-10	2.860E-10	2.860E-10	2.819E-10	2.873E-10	2.861E-10	2.861E-10	2.862E-10	2.784E-10	6.748E-15	2.852E-10	0.81
40 000	3.682E-10	3.670E-10	3.684E-10	3.682E-10	3.681E-10	3.660E-10	3.680E-10	3.680E-10	3.631E-10	3.689E-10	3.680E-10	3.680E-10	3.681E-10	3.566E-10	9.179E-16	3.668E-10	0.89
45 000	4.054E-10	4.041E-10	4.057E-10	4.054E-10	4.053E-10	4.029E-10	4.052E-10	4.052E-10	4.000E-10	4.060E-10	4.052E-10	4.052E-10	4.218E-10	3.974E-10	1.030E-14	4.053E-10	1.32
50 000	4.402E-10	4.388E-10	4.405E-10	4.402E-10	4.401E-10	4.376E-10	4.401E-10	4.401E-10	4.345E-10	4.408E-10	4.401E-10	4.401E-10	4.419E-10	4.322E-10	1.134E-14	4.391E-10	0.60
100 000	6.958E-10	6.934E-10	6.825E-10	6.957E-10	6.956E-10	6.916E-10	6.821E-10	6.821E-10	6.760E-10	6.962E-10	6.955E-10	6.955E-10	6.956E-10	6.512E-10	4.203E-23	6.868E-10	1.81
500 000	5.195E-10	5.173E-10	5.269E-10	5.194E-10	5.194E-10	5.164E-10	5.218E-10	5.218E-10	5.236E-10	5.201E-10	5.193E-10	5.193E-10	5.201E-10	5.136E-10	0.000E+00	5.203E-10	0.65
1000 000	2.140E-10	2.130E-10	2.169E-10	2.140E-10	2.140E-10	2.127E-10	2.147E-10	2.147E-10	2.149E-10	2.143E-10	2.139E-10	2.139E-10	2.140E-10	1.389E-10	0.000E+00	2.090E-10	9.66

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

[c] The sample mean and relative standard deviation do not include ^{210}Pb atom density results from the CINDER 90 calculations.

Figure 26. Relative difference from sample mean as a function of decay time for ^{210}Pb atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 47. ^{210}Pb half-life and associated uncertainty values

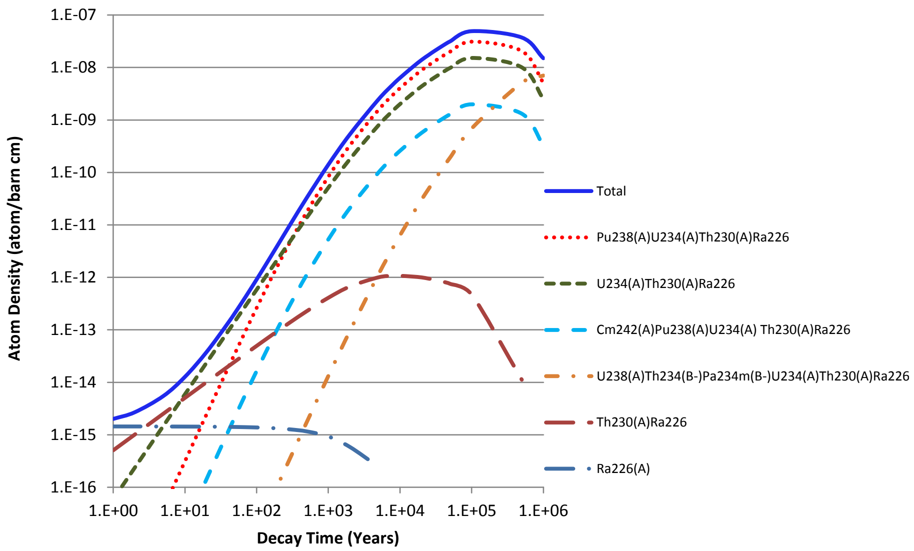
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	7.00579E+08	7.03719E+08	6.99302E+08	7.03719E+08	7.03700E+08
Uncertainty (s)	6.94267E+06	6.31139E+06	3.78683E+06	-	-

Sources: References 12–14, 20 and 21.

3.24. Time-dependent ^{226}Ra atom densities

^{226}Ra is a nuclide important for radiological dose assessments. This nuclide has a half-life of $1.6\times10^3 \pm 7$ years and decays by alpha-particle emission [20]. ^{226}Ra concentrations increase after fuel discharge and reach a maximum value at approximately 10^5 years due to a series of decay chains contributing to the formation of the ^{226}Ra nuclide, the most significant decay chains being $^{238}Pu(\alpha)^{234}U(\alpha)^{230}Th(\alpha)^{226}Ra$ and $^{234}U(\alpha)^{230}Th(\alpha)^{226}Ra$. The cumulative ^{226}Ra atom density and individual contributions from decay chains forming ^{226}Ra are shown as a function of decay time in Figure 27.

Figure 27. ^{226}Ra atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 48. In the table, the calculated ^{226}Ra atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{226}Ra using the evaluated decay codes/data libraries is illustrated in Figure 28. As seen in the figure, the ^{226}Ra atom density value at 10^6 years calculated with TIBSO is approximately 35% lower than the atom density values obtained using the other decay codes. ORIGEN-X-2008 result for 2×10^4 years is approximately 10% higher than the other results due to calculation approximations (see Appendix B). The ^{226}Ra half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 49.

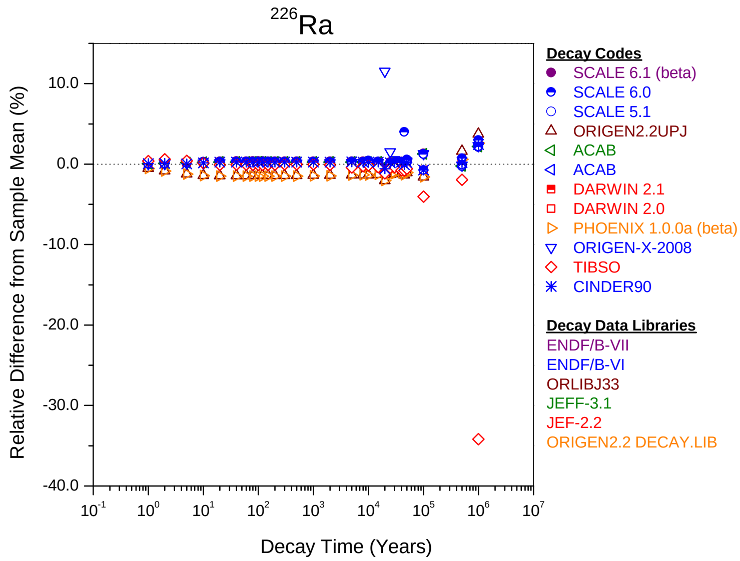
Table 48. Decay calculation results for ^{226}Ra (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	1.442E-15	0.00
1	2.007E-15	2.008E-15	1.996E-15	2.008E-15	2.008E-15	2.008E-15	2.008E-15	2.008E-15	1.996E-15	2.007E-15	2.007E-15	2.007E-15	2.008E-15	2.014E-15	2.007E-15	2.006E-15	0.24
2	2.693E-15	2.694E-15	2.668E-15	2.694E-15	2.694E-15	2.694E-15	2.693E-15	2.693E-15	2.668E-15	2.693E-15	2.693E-15	2.693E-15	2.694E-15	2.707E-15	2.693E-15	2.691E-15	0.38
5	5.492E-15	5.495E-15	5.415E-15	5.493E-15	5.492E-15	5.492E-15	5.492E-15	5.492E-15	5.414E-15	5.489E-15	5.491E-15	5.491E-15	5.493E-15	5.505E-15	5.483E-15	5.482E-15	0.53
10	1.275E-14	1.275E-14	1.254E-14	1.275E-14	1.274E-14	1.274E-14	1.274E-14	1.274E-14	1.253E-14	1.273E-14	1.274E-14	1.274E-14	1.275E-14	1.273E-14	1.274E-14	1.271E-14	0.60
20	3.778E-14	3.781E-14	3.714E-14	3.779E-14	3.778E-14	3.778E-14	3.777E-14	3.777E-14	3.712E-14	3.773E-14	3.777E-14	3.777E-14	3.778E-14	3.764E-14	3.777E-14	3.768E-14	0.62
40	1.360E-13	1.361E-13	1.337E-13	1.360E-13	1.359E-13	1.359E-13	1.359E-13	1.359E-13	1.336E-13	1.358E-13	1.359E-13	1.359E-13	1.360E-13	1.355E-13	1.359E-13	1.356E-13	0.63
60	3.084E-13	3.086E-13	3.032E-13	3.084E-13	3.083E-13	3.083E-13	3.082E-13	3.082E-13	3.029E-13	3.079E-13	3.083E-13	3.083E-13	3.084E-13	3.073E-13	3.083E-13	3.075E-13	0.62
80	5.654E-13	5.659E-13	5.559E-13	5.654E-13	5.652E-13	5.652E-13	5.651E-13	5.651E-13	5.554E-13	5.644E-13	5.652E-13	5.652E-13	5.655E-13	5.634E-13	5.653E-13	5.638E-13	0.62
100	9.157E-13	9.165E-13	9.003E-13	9.157E-13	9.155E-13	9.155E-13	9.153E-13	9.153E-13	8.995E-13	9.141E-13	9.154E-13	9.154E-13	9.158E-13	9.124E-13	9.156E-13	9.132E-13	0.62
120	1.367E-12	1.368E-12	1.344E-12	1.367E-12	1.366E-12	1.366E-12	1.366E-12	1.366E-12	1.342E-12	1.364E-12	1.366E-12	1.366E-12	1.367E-12	1.362E-12	1.366E-12	1.363E-12	0.62
150	2.244E-12	2.246E-12	2.207E-12	2.244E-12	2.244E-12	2.244E-12	2.243E-12	2.243E-12	2.205E-12	2.241E-12	2.243E-12	2.243E-12	2.244E-12	2.236E-12	2.244E-12	2.238E-12	0.61
200	4.280E-12	4.284E-12	4.209E-12	4.280E-12	4.279E-12	4.279E-12	4.279E-12	4.279E-12	4.205E-12	4.274E-12	4.279E-12	4.279E-12	4.280E-12	4.265E-12	4.280E-12	4.269E-12	0.61
300	1.065E-11	1.066E-11	1.047E-11	1.065E-11	1.065E-11	1.065E-11	1.065E-11	1.065E-11	1.047E-11	1.064E-11	1.065E-11	1.065E-11	1.065E-11	1.062E-11	1.065E-11	1.062E-11	0.61
500	3.293E-11	3.295E-11	3.238E-11	3.292E-11	3.292E-11	3.292E-11	3.291E-11	3.291E-11	3.235E-11	3.288E-11	3.291E-11	3.291E-11	3.292E-11	3.283E-11	3.292E-11	3.284E-11	0.61
1 000	1.408E-10	1.409E-10	1.385E-10	1.408E-10	1.408E-10	1.408E-10	1.407E-10	1.407E-10	1.384E-10	1.406E-10	1.407E-10	1.407E-10	1.408E-10	1.404E-10	1.408E-10	1.404E-10	0.60
2 000	5.335E-10	5.340E-10	5.248E-10	5.335E-10	5.334E-10	5.334E-10	5.333E-10	5.333E-10	5.244E-10	5.329E-10	5.333E-10	5.333E-10	5.335E-10	5.316E-10	5.334E-10	5.321E-10	0.60
5 000	2.466E-09	2.468E-09	2.427E-09	2.466E-09	2.466E-09	2.466E-09	2.465E-09	2.465E-09	2.426E-09	2.464E-09	2.465E-09	2.465E-09	2.466E-09	2.449E-09	2.466E-09	2.459E-09	0.59
8 000	4.789E-09	4.793E-09	4.713E-09	4.788E-09	4.788E-09	4.788E-09	4.787E-09	4.787E-09	4.712E-09	4.784E-09	4.787E-09	4.787E-09	4.788E-09	4.763E-09	4.788E-09	4.776E-09	0.58
10 000	6.369E-09	6.374E-09	6.269E-09	6.368E-09	6.367E-09	6.368E-09	6.367E-09	6.367E-09	6.268E-09	6.364E-09	6.366E-09	6.366E-09	6.381E-09	6.344E-09	6.368E-09	6.354E-09	0.58
15 000	1.023E-08	1.023E-08	1.007E-08	1.023E-08	1.022E-08	1.022E-08	1.022E-08	1.022E-08	1.007E-08	1.022E-08	1.022E-08	1.022E-08	1.022E-08	1.016E-08	1.022E-08	1.020E-08	0.56
20 000	1.388E-08	1.389E-08	1.367E-08	1.388E-08	1.387E-08	1.388E-08	1.387E-08	1.387E-08	1.367E-08	1.557E-08	1.387E-08	1.387E-08	1.387E-08	1.379E-08	1.388E-08	1.396E-08	3.35
25 000	1.731E-08	1.733E-08	1.706E-08	1.731E-08	1.731E-08	1.731E-08	1.731E-08	1.731E-08	1.706E-08	1.755E-08	1.731E-08	1.731E-08	1.731E-08	1.721E-08	1.731E-08	1.729E-08	0.68
30 000	2.055E-08	2.056E-08	2.026E-08	2.054E-08	2.054E-08	2.054E-08	2.054E-08	2.054E-08	2.026E-08	2.061E-08	2.054E-08	2.054E-08	2.054E-08	2.042E-08	2.054E-08	2.050E-08	0.53
40 000	2.643E-08	2.645E-08	2.608E-08	2.643E-08	2.642E-08	2.642E-08	2.642E-08	2.642E-08	2.608E-08	2.646E-08	2.642E-08	2.642E-08	2.642E-08	2.616E-08	2.643E-08	2.636E-08	0.53
45 000	2.910E-08	2.912E-08	2.873E-08	2.910E-08	2.909E-08	2.909E-08	2.909E-08	2.909E-08	2.872E-08	2.913E-08	2.909E-08	2.909E-08	3.028E-08	2.888E-08	2.910E-08	2.911E-08	1.25
50 000	3.160E-08	3.162E-08	3.121E-08	3.160E-08	3.159E-08	3.159E-08	3.159E-08	3.159E-08	3.121E-08	3.163E-08	3.159E-08	3.159E-08	3.172E-08	3.135E-08	3.160E-08	3.154E-08	0.50
100 000	4.994E-08	4.997E-08	4.853E-08	4.994E-08	4.993E-08	4.993E-08	4.895E-08	4.895E-08	4.853E-08	4.995E-08	4.992E-08	4.992E-08	4.993E-08	4.732E-08	4.895E-08	4.931E-08	1.66
500 000	3.729E-08	3.728E-08	3.797E-08	3.728E-08	3.728E-08	3.728E-08	3.743E-08	3.743E-08	3.758E-08	3.731E-08	3.727E-08	3.727E-08	3.733E-08	3.664E-08	3.743E-08	3.736E-08	0.77
1 000 000	1.536E-08	1.535E-08	1.560E-08	1.536E-08	1.536E-08	1.536E-08	1.540E-08	1.540E-08	1.542E-08	1.537E-08	1.535E-08	1.535E-08	1.536E-08	9.891E-09	1.540E-08	1.503E-08	9.80

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 28. Relative difference from sample mean as a function of decay time for ^{226}Ra atom density



1. Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.
2. Small deviations might occur in the ORIGEN-X-2008 calculated concentrations for times beyond 150 years due to a splitting of the calculation and due to the choice of large time steps.

Table 49. ^{226}Ra half-life and associated uncertainty values

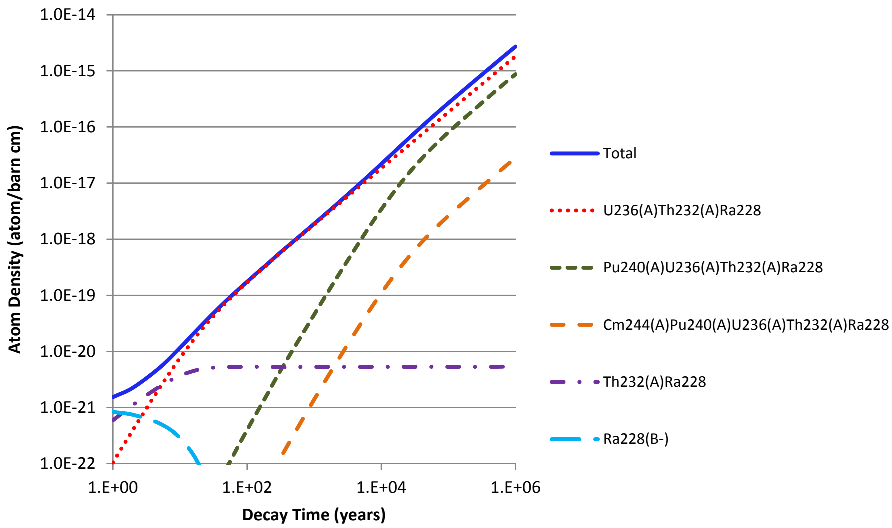
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	5.04921E+10	5.04911E+10	5.04911E+10	5.04911E+10	5.04900E+10
Uncertainty (s)	2.20903E+08	2.20899E+08	2.20898E+08	-	-

Sources: References 12–14, 20 and 21.

3.25. Time-dependent ^{228}Ra atom densities

^{228}Ra is a nuclide important for radiological dose assessments. This nuclide has a half-life of 5.75 ± 0.03 years and decays by beta-particle emission [20]. ^{228}Ra concentrations continuously increase after fuel discharge primarily due to the ^{236}U(α)^{232}Th(α)^{228}Ra decay chain. The cumulative ^{228}Ra atom density and individual contributions from decay chains forming ^{228}Ra are shown as a function of decay time in Figure 29.

Figure 29. ^{228}Ra atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

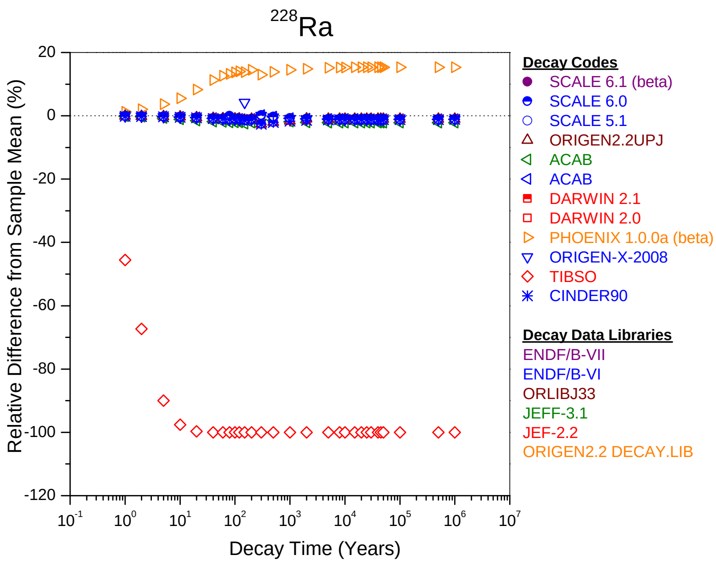
The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 50. In the table, the calculated ^{228}Ra atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. The TIBSO results shown in the table suggest that decay chains contributing to the formation of the ^{228}Ra nuclide may have not been considered by the code. A comparison of the results of the decay calculations for ^{228}Ra using the evaluated decay codes/data libraries is illustrated in Figure 30. The ^{228}Ra half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33,and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 51.

Table 50. Decay calculation results for ^{228}Ra (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean[c]	RSD (%)[c]
0	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	9.396E-22	0.00
1	1.528E-21	1.528E-21	1.528E-21	1.528E-21	1.528E-21	1.527E-21	1.528E-21	1.528E-21	1.548E-21	1.528E-21	1.528E-21	1.528E-21	1.528E-21	8.329E-22	1.527E-21	1.529E-21	0.35
2	2.256E-21	2.257E-21	2.257E-21	2.257E-21	2.257E-21	2.252E-21	2.257E-21	2.257E-21	2.305E-21	2.256E-21	2.256E-21	2.256E-21	2.257E-21	7.384E-22	2.255E-21	2.260E-21	0.58
5	5.132E-21	5.133E-21	5.133E-21	5.134E-21	5.133E-21	5.107E-21	5.134E-21	5.134E-21	5.331E-21	5.129E-21	5.132E-21	5.132E-21	5.133E-21	5.145E-22	5.128E-21	5.145E-21	1.05
10	1.155E-20	1.155E-20	1.155E-20	1.155E-20	1.155E-20	1.147E-20	1.156E-20	1.156E-20	1.224E-20	1.154E-20	1.155E-20	1.155E-20	1.155E-20	2.817E-22	1.154E-20	1.159E-20	1.61
20	2.750E-20	2.750E-20	2.750E-20	2.750E-20	2.750E-20	2.724E-20	2.751E-20	2.751E-20	2.994E-20	2.748E-20	2.749E-20	2.749E-20	2.750E-20	8.445E-23	2.748E-20	2.765E-20	2.39
40	6.309E-20	6.309E-20	6.310E-20	6.309E-20	6.308E-20	6.243E-20	6.311E-20	6.311E-20	7.074E-20	6.304E-20	6.307E-20	6.307E-20	6.309E-20	7.590E-24	6.304E-20	6.359E-20	3.25
60	9.953E-20	9.952E-20	9.954E-20	9.953E-20	9.951E-20	9.845E-20	9.956E-20	9.956E-20	1.131E-19	9.944E-20	9.950E-20	9.950E-20	9.950E-20	6.822E-25	9.945E-20	1.004E-19	3.64
80	1.361E-19	1.361E-19	1.361E-19	1.361E-19	1.361E-19	1.346E-19	1.361E-19	1.361E-19	1.556E-19	1.360E-19	1.360E-19	1.360E-19	1.374E-19	6.131E-26	1.360E-19	1.375E-19	3.83
100	1.727E-19	1.727E-19	1.727E-19	1.727E-19	1.726E-19	1.708E-19	1.727E-19	1.727E-19	1.983E-19	1.725E-19	1.726E-19	1.726E-19	1.728E-19	5.510E-27	1.725E-19	1.744E-19	3.96
120	2.093E-19	2.093E-19	2.093E-19	2.093E-19	2.093E-19	2.070E-19	2.094E-19	2.094E-19	2.409E-19	2.091E-19	2.092E-19	2.092E-19	2.093E-19	4.953E-28	2.091E-19	2.114E-19	4.04
150	2.643E-19	2.643E-19	2.644E-19	2.643E-19	2.643E-19	2.614E-19	2.644E-19	2.644E-19	3.050E-19	2.793E-19	2.642E-19	2.642E-19	2.643E-19	1.334E-29	2.641E-19	2.681E-19	4.26
200	3.562E-19	3.562E-19	3.562E-19	3.562E-19	3.561E-19	3.522E-19	3.563E-19	3.563E-19	4.121E-19	3.559E-19	3.561E-19	3.561E-19	3.562E-19	3.232E-32	3.559E-19	3.599E-19	4.19
300	5.560E-19	5.560E-19	5.407E-19	5.560E-19	5.559E-19	5.497E-19	5.409E-19	5.409E-19	6.270E-19	5.556E-19	5.558E-19	5.558E-19	5.560E-19	1.895E-37	5.402E-19	5.551E-19	3.95
500	9.278E-19	9.278E-19	9.125E-19	9.279E-19	9.277E-19	9.174E-19	9.127E-19	9.127E-19	1.060E-18	9.271E-19	9.275E-19	9.275E-19	9.278E-19	0.000E+00	9.117E-19	9.310E-19	4.07
1 000	1.873E-18	1.873E-18	1.858E-18	1.873E-18	1.873E-18	1.852E-18	1.858E-18	1.858E-18	2.161E-18	1.872E-18	1.873E-18	1.873E-18	1.873E-18	0.000E+00	1.856E-18	1.888E-18	4.20
2 000	3.828E-18	3.828E-18	3.829E-18	3.828E-18	3.828E-18	3.785E-18	3.813E-18	3.813E-18	4.439E-18	3.825E-18	3.827E-18	3.827E-18	3.828E-18	0.000E+00	3.809E-18	3.865E-18	4.29
5 000	1.013E-17	1.013E-17	1.013E-17	1.013E-17	1.013E-17	1.001E-17	1.012E-17	1.012E-17	1.178E-17	1.012E-17	1.013E-17	1.013E-17	1.013E-17	0.000E+00	1.010E-17	1.023E-17	4.37
8 000	1.694E-17	1.694E-17	1.695E-17	1.694E-17	1.694E-17	1.675E-17	1.693E-17	1.693E-17	1.973E-17	1.693E-17	1.694E-17	1.694E-17	1.694E-17	0.000E+00	1.691E-17	1.712E-17	4.39
10 000	2.170E-17	2.170E-17	2.171E-17	2.170E-17	2.170E-17	2.146E-17	2.169E-17	2.169E-17	2.528E-17	2.168E-17	2.170E-17	2.170E-17	2.170E-17	0.000E+00	2.167E-17	2.193E-17	4.40
15 000	3.413E-17	3.413E-17	3.414E-17	3.413E-17	3.413E-17	3.374E-17	3.412E-17	3.412E-17	3.977E-17	3.410E-17	3.412E-17	3.412E-17	3.413E-17	0.000E+00	3.408E-17	3.450E-17	4.41
20 000	4.706E-17	4.706E-17	4.707E-17	4.706E-17	4.706E-17	4.653E-17	4.706E-17	4.706E-17	5.485E-17	4.702E-17	4.705E-17	4.705E-17	4.706E-17	0.000E+00	4.700E-17	4.757E-17	4.41
25 000	6.028E-17	6.029E-17	6.030E-17	6.029E-17	6.028E-17	5.961E-17	6.029E-17	6.029E-17	7.027E-17	6.024E-17	6.027E-17	6.027E-17	6.029E-17	0.000E+00	6.022E-17	6.094E-17	4.41
30 000	7.368E-17	7.369E-17	7.370E-17	7.369E-17	7.368E-17	7.285E-17	7.370E-17	7.370E-17	8.590E-17	7.363E-17	7.367E-17	7.367E-17	7.369E-17	0.000E+00	7.361E-17	7.449E-17	4.42
40 000	1.007E-16	1.008E-16	1.008E-16	1.008E-16	1.007E-16	9.961E-17	1.008E-16	1.008E-16	1.175E-16	1.007E-16	1.007E-16	1.007E-16	1.007E-16	0.000E+00	1.007E-16	1.018E-16	4.42
45 000	1.143E-16	1.143E-16	1.144E-16	1.144E-16	1.143E-16	1.131E-16	1.144E-16	1.144E-16	1.333E-16	1.143E-16	1.143E-16	1.143E-16	1.143E-16	0.000E+00	1.142E-16	1.156E-16	4.42
50 000	1.279E-16	1.280E-16	1.280E-16	1.280E-16	1.280E-16	1.265E-16	1.280E-16	1.280E-16	1.492E-16	1.279E-16	1.279E-16	1.279E-16	1.280E-16	0.000E+00	1.278E-16	1.294E-16	4.42
100 000	2.642E-16	2.642E-16	2.643E-16	2.643E-16	2.642E-16	2.613E-16	2.643E-16	2.643E-16	3.081E-16	2.641E-16	2.642E-16	2.642E-16	2.642E-16	0.000E+00	2.640E-16	2.672E-16	4.42
500 000	1.348E-15	1.348E-15	1.348E-15	1.348E-15	1.348E-15	1.333E-15	1.348E-15	1.348E-15	1.571E-15	1.347E-15	1.347E-15	1.347E-15	1.348E-15	0.000E+00	1.347E-15	1.363E-15	4.41
1 000 000	2.684E-15	2.684E-15	2.685E-15	2.684E-15	2.684E-15	2.654E-15	2.685E-15	2.685E-15	3.129E-15	2.682E-15	2.683E-15	2.683E-15	2.684E-15	0.000E+00	2.682E-15	2.714E-15	4.41

[a] ENDF/B-VI decay data.
[b] JEFF-3.1 decay data.
[c] Sample mean and relative standard deviation do not include the ^{228}Ra atom density values obtained using TIBSO.

Figure 30. Relative difference from sample mean as a function of decay time for ^{228}Ra atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 51. ^{228}Ra half-life and associated uncertainty values

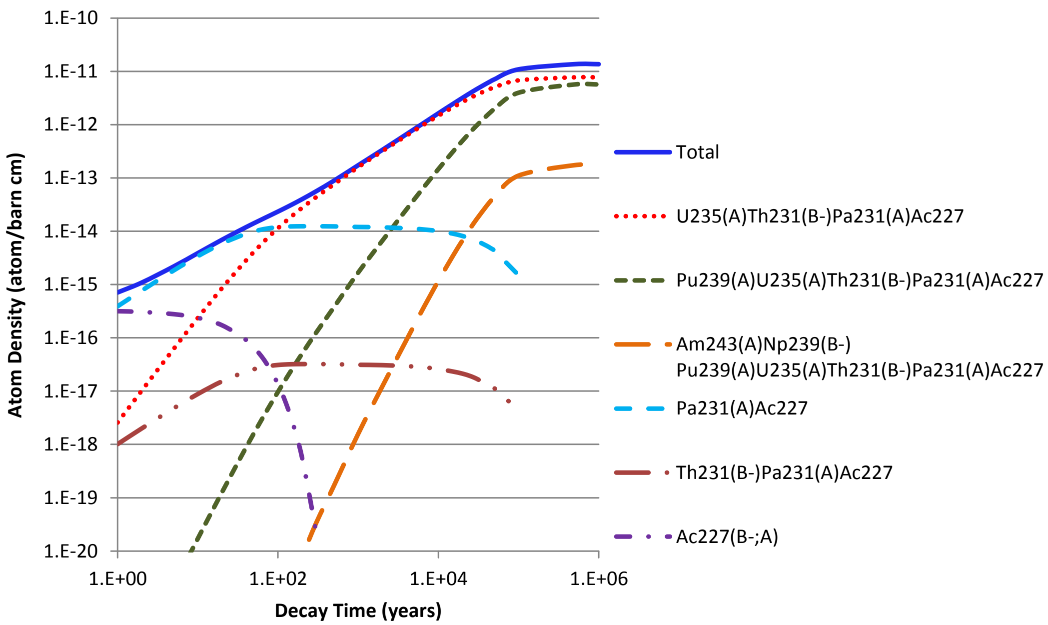
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.81456E+08	1.81452E+08	1.81456E+08	1.814523E+08	1.81456E+08	2.11431E+08
Uncertainty (s)	9.46728E+05	9.46708E+05	9.46728E+05	-	9.46728E+05	-

Sources: References 12–14, 20 and 21.

3.26. Time-dependent ^{227}Ac atom densities

^{227}Ac is an actinide important for radiological dose assessments. This nuclide has a half-life value of 21.772 ± 0.003 years and decays by beta- and alpha-particle emissions [20]. ^{227}Ac concentrations continuously increase after fuel discharge due to ^{231}Pa ($T_{1/2}$ = 3.276×10^{4} ± 110 years) alpha decay and due to a series of decay chains, the most predominant of which are ^{235}U(α)^{231}Th(β^{-})^{231}Pa(α)^{227}Ac and ^{239}Pu(α)^{235}U(α)^{231}Th(β^{-})^{231}Pa(α)^{227}Ac. The cumulative ^{227}Ac atom density and individual contributions from decay chains forming ^{227}Ac are shown as a function of decay time in Figure 31.

Figure 31. ^{227}Ac atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 52. In the table, the calculated ^{227}Ac atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{227}Ac using the evaluated decay codes/data libraries is illustrated in Figure 32. A small dispersion of the results is observed at 10^{3} years (RSD ≈ 2%). In addition, TIBSO results have a larger deviation from the other results for the decay time interval between 10^{3} and 10^{5} years. The ^{227}Ac half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 53.

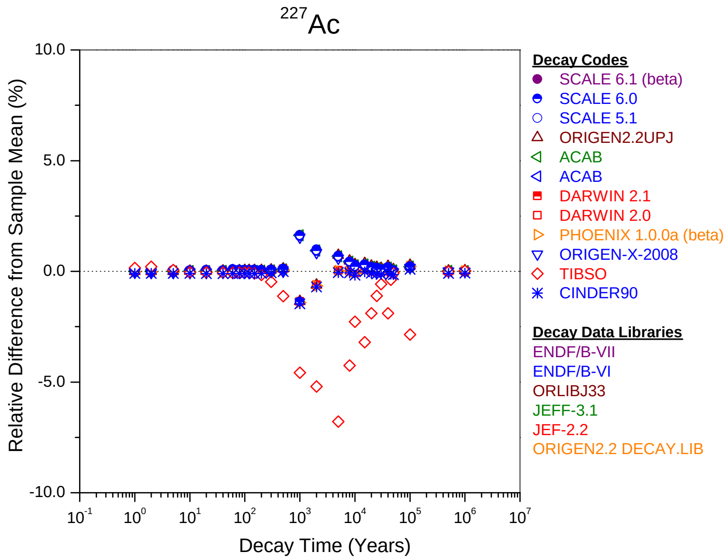
Table 52. Decay calculation results for ^{227}Ac (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.259E-16	3.256E-16	3.259E-16	0.00
1	7.093E-16	7.095E-16	7.095E-16	7.095E-16	7.095E-16	7.095E-16	7.095E-16	7.095E-16	7.093E-16	7.092E-16	7.093E-16	7.093E-16	7.095E-16	7.105E-16	7.088E-16	7.095E-16	0.04
2	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.086E-15	1.088E-15	1.085E-15	1.086E-15	0.06
5	2.177E-15	2.177E-15	2.177E-15	2.177E-15	2.177E-15	2.177E-15	2.177E-15	2.177E-15	2.176E-15	2.175E-15	2.176E-15	2.176E-15	2.177E-15	2.178E-15	2.175E-15	2.177E-15	0.03
10	3.876E-15	3.876E-15	3.875E-15	3.876E-15	3.875E-15	3.876E-15	3.875E-15	3.875E-15	3.874E-15	3.873E-15	3.875E-15	3.875E-15	3.876E-15	3.873E-15	3.871E-15	3.875E-15	0.03
20	6.903E-15	6.903E-15	6.902E-15	6.903E-15	6.902E-15	6.902E-15	6.902E-15	6.902E-15	6.899E-15	6.897E-15	6.900E-15	6.900E-15	6.902E-15	6.898E-15	6.894E-15	6.901E-15	0.03
40	1.192E-14	1.192E-14	1.192E-14	1.192E-14	1.192E-14	1.192E-14	1.192E-14	1.192E-14	1.191E-14	1.191E-14	1.191E-14	1.191E-14	1.192E-14	1.191E-14	1.190E-14	1.191E-14	0.04
60	1.611E-14	1.611E-14	1.611E-14	1.611E-14	1.611E-14	1.611E-14	1.611E-14	1.611E-14	1.610E-14	1.610E-14	1.610E-14	1.610E-14	1.610E-14	1.609E-14	1.609E-14	1.610E-14	0.04
80	1.986E-14	1.986E-14	1.986E-14	1.986E-14	1.986E-14	1.986E-14	1.986E-14	1.986E-14	1.985E-14	1.984E-14	1.985E-14	1.985E-14	1.985E-14	1.984E-14	1.983E-14	1.985E-14	0.04
100	2.338E-14	2.338E-14	2.338E-14	2.338E-14	2.338E-14	2.338E-14	2.338E-14	2.338E-14	2.337E-14	2.336E-14	2.337E-14	2.337E-14	2.337E-14	2.336E-14	2.335E-14	2.337E-14	0.03
120	2.678E-14	2.678E-14	2.678E-14	2.678E-14	2.678E-14	2.678E-14	2.678E-14	2.678E-14	2.676E-14	2.676E-14	2.677E-14	2.677E-14	2.677E-14	2.676E-14	2.674E-14	2.677E-14	0.03
150	3.177E-14	3.176E-14	3.177E-14	3.176E-14	3.176E-14	3.176E-14	3.176E-14	3.176E-14	3.175E-14	3.173E-14	3.175E-14	3.175E-14	3.176E-14	3.173E-14	3.172E-14	3.176E-14	0.05
200	3.996E-14	3.996E-14	3.997E-14	3.996E-14	3.996E-14	3.996E-14	3.996E-14	3.996E-14	3.994E-14	3.993E-14	3.995E-14	3.995E-14	3.996E-14	3.989E-14	3.992E-14	3.995E-14	0.06
300	5.628E-14	5.628E-14	5.629E-14	5.628E-14	5.627E-14	5.628E-14	5.628E-14	5.628E-14	5.625E-14	5.623E-14	5.626E-14	5.626E-14	5.626E-14	5.599E-14	5.621E-14	5.625E-14	0.14
500	8.889E-14	8.888E-14	8.890E-14	8.889E-14	8.887E-14	8.889E-14	8.889E-14	8.889E-14	8.885E-14	8.880E-14	8.886E-14	8.886E-14	8.888E-14	8.780E-14	8.879E-14	8.880E-14	0.33
1 000	1.756E-13	1.756E-13	1.704E-13	1.756E-13	1.756E-13	1.756E-13	1.704E-13	1.704E-13	1.703E-13	1.754E-13	1.755E-13	1.755E-13	1.756E-13	1.649E-13	1.702E-13	1.728E-13	1.98
2 000	3.386E-13	3.386E-13	3.334E-13	3.386E-13	3.386E-13	3.386E-13	3.334E-13	3.334E-13	3.333E-13	3.383E-13	3.385E-13	3.385E-13	3.386E-13	3.180E-13	3.331E-13	3.354E-13	1.67
5 000	8.265E-13	8.264E-13	8.269E-13	8.265E-13	8.264E-13	8.265E-13	8.213E-13	8.213E-13	8.211E-13	8.257E-13	8.262E-13	8.262E-13	8.264E-13	7.652E-13	8.204E-13	8.209E-13	1.97
8 000	1.311E-12	1.311E-12	1.312E-12	1.311E-12	1.311E-12	1.311E-12	1.306E-12	1.306E-12	1.306E-12	1.310E-12	1.311E-12	1.311E-12	1.311E-12	1.250E-12	1.304E-12	1.305E-12	1.24
10 000	1.632E-12	1.632E-12	1.632E-12	1.632E-12	1.632E-12	1.632E-12	1.626E-12	1.626E-12	1.626E-12	1.630E-12	1.631E-12	1.631E-12	1.631E-12	1.590E-12	1.624E-12	1.627E-12	0.67
15 000	2.419E-12	2.419E-12	2.420E-12	2.419E-12	2.419E-12	2.419E-12	2.414E-12	2.414E-12	2.413E-12	2.417E-12	2.418E-12	2.418E-12	2.419E-12	2.334E-12	2.411E-12	2.412E-12	0.93
20 000	3.183E-12	3.183E-12	3.184E-12	3.183E-12	3.183E-12	3.183E-12	3.177E-12	3.177E-12	3.177E-12	3.179E-12	3.182E-12	3.182E-12	3.183E-12	3.116E-12	3.174E-12	3.176E-12	0.55
25 000	3.918E-12	3.918E-12	3.920E-12	3.918E-12	3.918E-12	3.918E-12	3.912E-12	3.912E-12	3.913E-12	3.915E-12	3.917E-12	3.917E-12	3.918E-12	3.870E-12	3.908E-12	3.913E-12	0.33
30 000	4.621E-12	4.621E-12	4.623E-12	4.621E-12	4.621E-12	4.621E-12	4.615E-12	4.615E-12	4.616E-12	4.618E-12	4.620E-12	4.620E-12	4.621E-12	4.590E-12	4.611E-12	4.617E-12	0.18
40 000	5.923E-12	5.923E-12	5.926E-12	5.923E-12	5.922E-12	5.923E-12	5.917E-12	5.917E-12	5.918E-12	5.918E-12	5.921E-12	5.921E-12	5.923E-12	5.801E-12	5.911E-12	5.913E-12	0.55
45 000	6.520E-12	6.520E-12	6.523E-12	6.521E-12	6.520E-12	6.521E-12	6.514E-12	6.514E-12	6.515E-12	6.516E-12	6.518E-12	6.518E-12	6.517E-12	6.491E-12	6.507E-12	6.516E-12	0.12
50 000	7.081E-12	7.081E-12	7.084E-12	7.081E-12	7.080E-12	7.081E-12	7.074E-12	7.074E-12	7.076E-12	7.076E-12	7.079E-12	7.079E-12	7.081E-12	7.072E-12	7.067E-12	7.078E-12	0.05
100 000	1.092E-11	1.092E-11	1.093E-11	1.092E-11	1.092E-11	1.092E-11	1.092E-11	1.092E-11	1.092E-11	1.091E-11	1.091E-11	1.091E-11	1.092E-11	1.058E-11	1.090E-11	1.089E-11	0.82
500 000	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.362E-11	1.361E-11	1.362E-11	1.361E-11	1.362E-11	0.01
1 000 000	1.361E-11	1.361E-11	1.362E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.361E-11	1.360E-11	1.361E-11	0.01

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 32. Relative difference from sample mean as a function of decay time for ^{227}Ac atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 53. ^{227}Ac half-life and associated uncertainty values

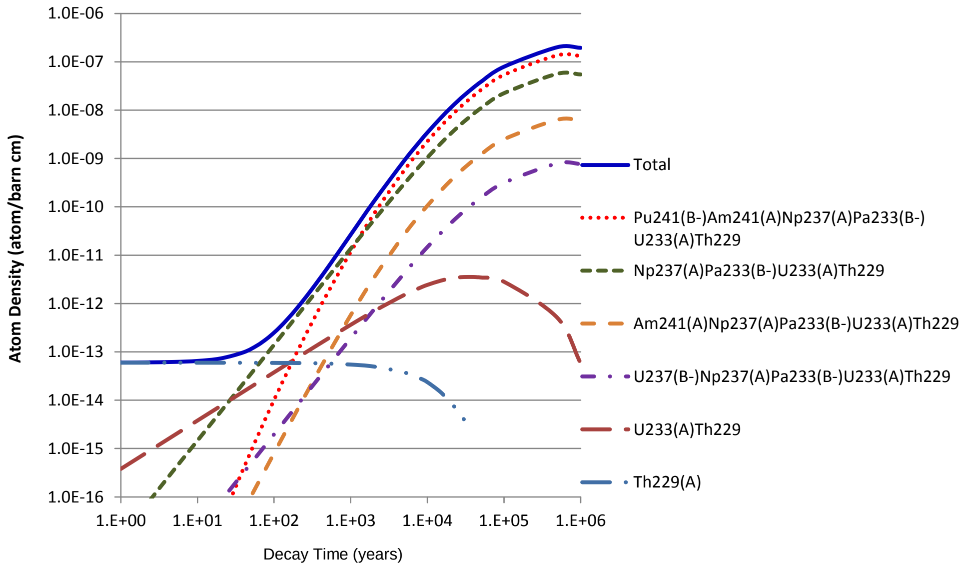
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	6.87072E+08	6.86994E+08	6.87104E+08	6.86994E+08	6.87100E+08
Uncertainty (s)	9.46728E+04	9.46708E+05	9.46728E+04	-	-

Sources: References 12–14, 20 and 21.

3.27. Time-dependent ^{229}Th atom densities

^{229}Th is an actinide important for radiological dose assessments. This nuclide has a half-life of $7.34\times10^3 \pm 160$ years and decays by alpha-particle emission [20]. ^{229}Th concentrations increase after fuel discharge due to a series of decay chains contributing to the formation of the ^{229}Th nuclide. The cumulative ^{229}Th atom density and individual contributions from decay chains forming ^{229}Th are shown as a function of decay time in Figure 33.

Figure 33. ^{229}Th atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 54. In the table, the calculated ^{229}Th atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{229}Th using the evaluated decay codes/data libraries is illustrated in Figure 34. Significant dispersion of the results is observed after approximately 150 years from fuel discharge primarily due to ORIGEN-X-2008 calculation approximations (see Appendix B) and due to the difference between the ENDF/B-VI ^{229}Th half-life value and the ^{229}Th half-life values in the other decay data libraries. The ^{229}Th half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 55.

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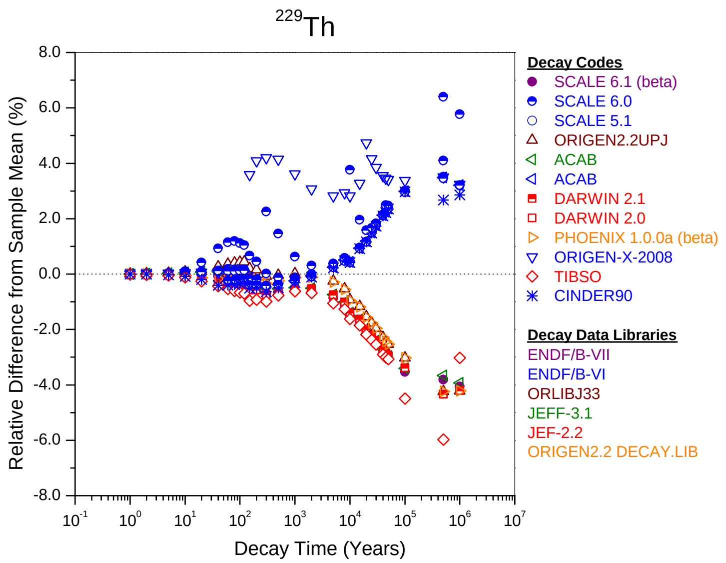
Table 54. Decay calculation results for ^{229}Th (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	5.965E-14	0.00
1	6.003E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.004E-14	6.002E-14	6.004E-14	6.003E-14	6.004E-14	6.004E-14	0.01
2	6.045E-14	6.045E-14	6.046E-14	6.046E-14	6.046E-14	6.046E-14	6.045E-14	6.045E-14	6.045E-14	6.046E-14	6.045E-14	6.044E-14	6.046E-14	6.044E-14	6.045E-14	6.045E-14	0.01
5	6.187E-14	6.188E-14	6.191E-14	6.190E-14	6.190E-14	6.189E-14	6.186E-14	6.186E-14	6.187E-14	6.190E-14	6.188E-14	6.188E-14	6.190E-14	6.185E-14	6.186E-14	6.188E-14	0.03
10	6.483E-14	6.483E-14	6.489E-14	6.487E-14	6.487E-14	6.487E-14	6.478E-14	6.478E-14	6.480E-14	6.487E-14	6.490E-14	6.486E-14	6.487E-14	6.476E-14	6.478E-14	6.484E-14	0.07
20	7.291E-14	7.290E-14	7.303E-14	7.298E-14	7.298E-14	7.296E-14	7.277E-14	7.277E-14	7.282E-14	7.297E-14	7.322E-14	7.296E-14	7.298E-14	7.273E-14	7.277E-14	7.292E-14	0.17
40	9.791E-14	9.785E-14	9.818E-14	9.804E-14	9.804E-14	9.800E-14	9.759E-14	9.759E-14	9.775E-14	9.800E-14	9.883E-14	9.801E-14	9.804E-14	9.750E-14	9.752E-14	9.792E-14	0.33
60	1.353E-13	1.351E-13	1.357E-13	1.355E-13	1.355E-13	1.354E-13	1.348E-13	1.348E-13	1.351E-13	1.354E-13	1.368E-13	1.354E-13	1.349E-13	1.345E-13	1.347E-13	1.353E-13	0.41
80	1.857E-13	1.855E-13	1.864E-13	1.860E-13	1.860E-13	1.859E-13	1.850E-13	1.850E-13	1.855E-13	1.858E-13	1.879E-13	1.859E-13	1.853E-13	1.846E-13	1.850E-13	1.857E-13	0.43
100	2.501E-13	2.497E-13	2.511E-13	2.504E-13	2.504E-13	2.502E-13	2.491E-13	2.491E-13	2.499E-13	2.501E-13	2.528E-13	2.503E-13	2.495E-13	2.483E-13	2.492E-13	2.500E-13	0.42
120	3.291E-13	3.285E-13	3.304E-13	3.295E-13	3.294E-13	3.292E-13	3.278E-13	3.278E-13	3.289E-13	3.291E-13	3.324E-13	3.294E-13	3.284E-13	3.267E-13	3.280E-13	3.290E-13	0.40
150	4.767E-13	4.759E-13	4.787E-13	4.772E-13	4.771E-13	4.767E-13	4.750E-13	4.750E-13	4.767E-13	4.949E-13	4.809E-13	4.770E-13	4.758E-13	4.731E-13	4.753E-13	4.777E-13	1.09
200	8.064E-13	8.048E-13	8.097E-13	8.070E-13	8.069E-13	8.061E-13	8.038E-13	8.038E-13	8.068E-13	8.414E-13	8.121E-13	8.068E-13	8.052E-13	8.009E-13	8.044E-13	8.084E-13	1.21
300	1.816E-12	1.812E-12	1.823E-12	1.817E-12	1.817E-12	1.815E-12	1.811E-12	1.811E-12	1.818E-12	1.901E-12	1.825E-12	1.817E-12	1.866E-12	1.807E-12	1.813E-12	1.825E-12	1.43
500	5.482E-12	5.467E-12	5.500E-12	5.483E-12	5.482E-12	5.473E-12	5.467E-12	5.467E-12	5.489E-12	5.731E-12	5.496E-12	5.481E-12	5.583E-12	5.460E-12	5.475E-12	5.502E-12	1.30
1 000	2.648E-11	2.638E-11	2.655E-11	2.649E-11	2.648E-11	2.641E-11	2.640E-11	2.640E-11	2.651E-11	2.750E-11	2.651E-11	2.648E-11	2.671E-11	2.638E-11	2.646E-11	2.654E-11	1.08
2 000	1.282E-10	1.275E-10	1.283E-10	1.283E-10	1.282E-10	1.277E-10	1.276E-10	1.276E-10	1.282E-10	1.323E-10	1.283E-10	1.282E-10	1.287E-10	1.274E-10	1.282E-10	1.283E-10	0.93
5 000	9.074E-10	8.972E-10	9.028E-10	9.075E-10	9.073E-10	8.983E-10	8.983E-10	8.983E-10	9.024E-10	9.306E-10	9.075E-10	9.072E-10	9.085E-10	8.955E-10	9.070E-10	9.050E-10	0.97
8 000	2.274E-09	2.237E-09	2.250E-09	2.274E-09	2.274E-09	2.240E-09	2.240E-09	2.240E-09	2.250E-09	2.329E-09	2.274E-09	2.273E-09	2.276E-09	2.234E-09	2.273E-09	2.262E-09	1.13
10 000	3.438E-09	3.371E-09	3.391E-09	3.438E-09	3.438E-09	3.375E-09	3.375E-09	3.375E-09	3.390E-09	3.519E-09	3.438E-09	3.437E-09	3.551E-09	3.367E-09	3.437E-09	3.423E-09	1.65
15 000	6.989E-09	6.802E-09	6.843E-09	6.990E-09	6.989E-09	6.811E-09	6.811E-09	6.811E-09	6.842E-09	7.150E-09	6.990E-09	6.988E-09	7.059E-09	6.796E-09	6.987E-09	6.924E-09	1.67
20 000	1.115E-08	1.079E-08	1.085E-08	1.115E-08	1.115E-08	1.080E-08	1.080E-08	1.080E-08	1.085E-08	1.154E-08	1.115E-08	1.115E-08	1.120E-08	1.078E-08	1.115E-08	1.102E-08	2.10
25 000	1.567E-08	1.508E-08	1.517E-08	1.567E-08	1.567E-08	1.510E-08	1.510E-08	1.510E-08	1.516E-08	1.608E-08	1.567E-08	1.567E-08	1.569E-08	1.507E-08	1.567E-08	1.544E-08	2.21
30 000	2.037E-08	1.951E-08	1.963E-08	2.037E-08	2.037E-08	1.954E-08	1.954E-08	1.954E-08	1.963E-08	2.079E-08	2.037E-08	2.037E-08	2.038E-08	1.951E-08	2.036E-08	2.002E-08	2.34
40 000	2.993E-08	2.848E-08	2.864E-08	2.994E-08	2.993E-08	2.852E-08	2.852E-08	2.852E-08	2.864E-08	3.035E-08	2.994E-08	2.993E-08	2.994E-08	2.846E-08	2.993E-08	2.931E-08	2.61
45 000	3.469E-08	3.291E-08	3.310E-08	3.469E-08	3.469E-08	3.296E-08	3.296E-08	3.296E-08	3.310E-08	3.510E-08	3.469E-08	3.468E-08	3.477E-08	3.291E-08	3.468E-08	3.392E-08	2.74
50 000	3.938E-08	3.728E-08	3.749E-08	3.938E-08	3.938E-08	3.733E-08	3.733E-08	3.733E-08	3.749E-08	3.978E-08	3.938E-08	3.937E-08	3.942E-08	3.728E-08	3.937E-08	3.847E-08	2.82
100 000	8.131E-08	7.616E-08	7.656E-08	8.132E-08	8.131E-08	7.626E-08	7.627E-08	7.627E-08	7.656E-08	8.161E-08	8.132E-08	8.129E-08	8.128E-08	7.540E-08	8.129E-08	7.895E-08	3.39
500 000	2.076E-07	1.930E-07	1.922E-07	2.077E-07	2.077E-07	1.933E-07	1.919E-07	1.919E-07	1.922E-07	2.077E-07	2.135E-07	2.076E-07	2.089E-07	1.887E-07	2.060E-07	2.007E-07	4.43
1 000 000	2.006E-07	1.865E-07	1.862E-07	2.006E-07	2.006E-07	1.868E-07	1.862E-07	1.862E-07	1.862E-07	2.007E-07	2.056E-07	2.006E-07	2.006E-07	1.885E-07	1.999E-07	1.944E-07	3.99

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 34. Relative difference from sample mean as a function of decay time for ^{229}Th atom density



1. Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.
2. Small deviations might occur in the ORIGEN-X-2008 calculated concentrations for times beyond 150 years due to a splitting of the calculation and due to the choice of large time steps.

Table 55. ^{229}Th half-life and associated uncertainty values

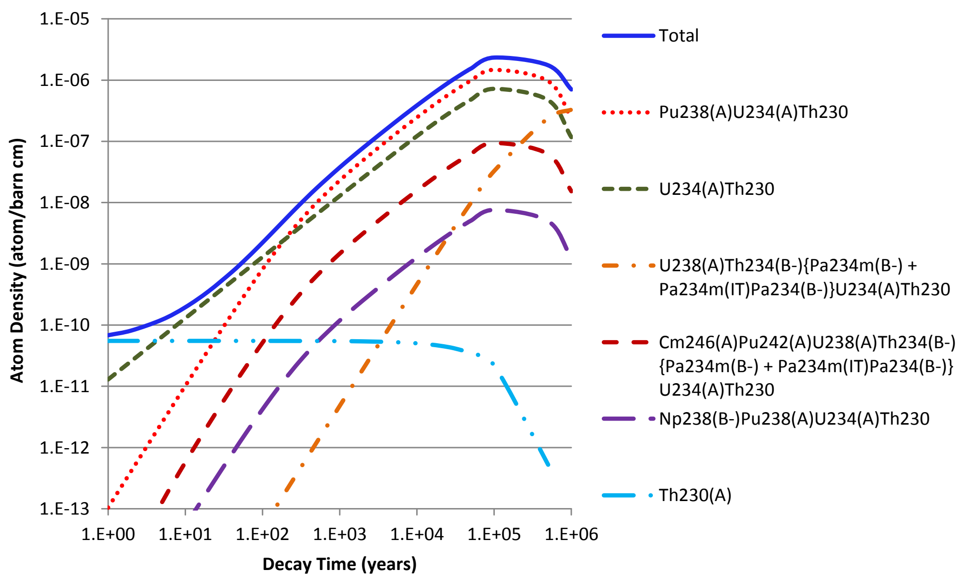
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.31632E+11	2.48667E+11	2.31633E+11	2.31628E+11	2.31600E+11
Uncertainty (s)	5.04922E+09	1.26227E+09	5.04922E+09	-	-

Sources: References 12–14, 20 and 21.

3.28. Time-dependent ^{230}Th atom densities

^{230}Th is an actinide important for public dose assessments. This nuclide has a half-life of $7.538\times10^4 \pm 30$ years and decays by alpha-particle emission [20]. ^{230}Th concentrations increase after fuel discharge primarily due to ^{238}Pu and ^{234}U alpha decay and due to a series of decay chains contributing to the formation of the ^{230}Th nuclide. The cumulative ^{230}Th atom density and individual contributions from decay chains forming ^{230}Th are shown as a function of decay time in Figure 35.

Figure 35. ^{230}Th atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 56. In the table, the calculated ^{230}Th atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{230}Th using the evaluated decay codes/data libraries is illustrated in Figure 36. As seen in the figure, ^{230}Th atom densities at long decay times calculated using TIBSO significantly differ (e.g. ~ 50% lower at 10^6 years) from the ^{230}Th atom densities calculated using the other evaluated decay codes/libraries. The ^{230}Th half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 57.

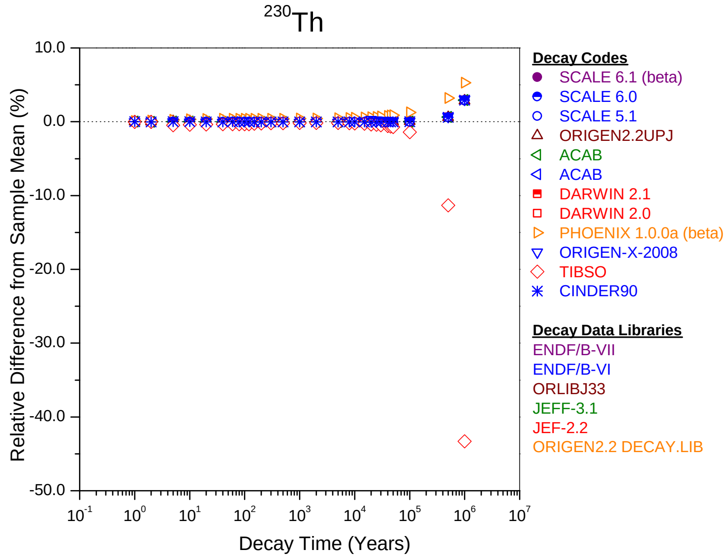
Table 56. Decay calculation results for ^{230}Th (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	5.510E-11	0.00
1	6.810E-11	6.812E-11	6.812E-11	6.811E-11	6.811E-11	6.811E-11	6.811E-11	6.811E-11	6.816E-11	6.810E-11	6.811E-11	6.809E-11	6.811E-11	6.810E-11	6.811E-11	6.811E-11	0.03
2	8.133E-11	8.135E-11	8.135E-11	8.133E-11	8.133E-11	8.133E-11	8.133E-11	8.133E-11	8.145E-11	8.131E-11	8.133E-11	8.131E-11	8.133E-11	8.131E-11	8.133E-11	8.134E-11	0.04
5	1.223E-10	1.224E-10	1.224E-10	1.223E-10	1.223E-10	1.223E-10	1.223E-10	1.223E-10	1.226E-10	1.223E-10	1.223E-10	1.223E-10	1.223E-10	1.217E-10	1.223E-10	1.223E-10	0.15
10	1.949E-10	1.950E-10	1.950E-10	1.949E-10	1.949E-10	1.949E-10	1.949E-10	1.949E-10	1.955E-10	1.948E-10	1.949E-10	1.948E-10	1.949E-10	1.941E-10	1.949E-10	1.949E-10	0.15
20	3.553E-10	3.555E-10	3.555E-10	3.553E-10	3.552E-10	3.552E-10	3.553E-10	3.553E-10	3.566E-10	3.550E-10	3.553E-10	3.552E-10	3.553E-10	3.540E-10	3.553E-10	3.553E-10	0.15
40	7.318E-10	7.323E-10	7.322E-10	7.318E-10	7.317E-10	7.317E-10	7.317E-10	7.317E-10	7.346E-10	7.311E-10	7.317E-10	7.315E-10	7.317E-10	7.293E-10	7.317E-10	7.318E-10	0.15
60	1.173E-09	1.174E-09	1.174E-09	1.173E-09	1.173E-09	1.173E-09	1.173E-09	1.173E-09	1.178E-09	1.172E-09	1.173E-09	1.173E-09	1.174E-09	1.169E-09	1.173E-09	1.173E-09	0.15
80	1.671E-09	1.672E-09	1.672E-09	1.671E-09	1.670E-09	1.670E-09	1.670E-09	1.670E-09	1.677E-09	1.669E-09	1.670E-09	1.670E-09	1.671E-09	1.665E-09	1.670E-09	1.671E-09	0.15
100	2.215E-09	2.217E-09	2.217E-09	2.215E-09	2.215E-09	2.215E-09	2.215E-09	2.215E-09	2.224E-09	2.213E-09	2.215E-09	2.215E-09	2.215E-09	2.208E-09	2.215E-09	2.215E-09	0.15
120	2.801E-09	2.803E-09	2.803E-09	2.801E-09	2.800E-09	2.800E-09	2.800E-09	2.800E-09	2.812E-09	2.798E-09	2.800E-09	2.800E-09	2.801E-09	2.792E-09	2.800E-09	2.801E-09	0.15
150	3.742E-09	3.745E-09	3.744E-09	3.742E-09	3.741E-09	3.741E-09	3.741E-09	3.741E-09	3.757E-09	3.739E-09	3.741E-09	3.740E-09	3.742E-09	3.732E-09	3.741E-09	3.742E-09	0.14
200	5.441E-09	5.445E-09	5.444E-09	5.440E-09	5.440E-09	5.440E-09	5.440E-09	5.440E-09	5.462E-09	5.437E-09	5.440E-09	5.439E-09	5.440E-09	5.428E-09	5.440E-09	5.441E-09	0.13
300	9.148E-09	9.155E-09	9.154E-09	9.148E-09	9.146E-09	9.146E-09	9.147E-09	9.147E-09	9.185E-09	9.141E-09	9.147E-09	9.145E-09	9.148E-09	9.129E-09	9.147E-09	9.149E-09	0.13
500	1.709E-08	1.711E-08	1.710E-08	1.709E-08	1.709E-08	1.709E-08	1.709E-08	1.709E-08	1.716E-08	1.708E-08	1.709E-08	1.709E-08	1.709E-08	1.706E-08	1.709E-08	1.710E-08	0.13
1 000	3.748E-08	3.751E-08	3.751E-08	3.748E-08	3.747E-08	3.748E-08	3.748E-08	3.748E-08	3.764E-08	3.746E-08	3.748E-08	3.747E-08	3.748E-08	3.743E-08	3.748E-08	3.749E-08	0.13
2 000	7.804E-08	7.810E-08	7.809E-08	7.804E-08	7.803E-08	7.803E-08	7.803E-08	7.803E-08	7.839E-08	7.799E-08	7.803E-08	7.801E-08	7.803E-08	7.794E-08	7.803E-08	7.805E-08	0.13
5 000	1.969E-07	1.970E-07	1.970E-07	1.969E-07	1.968E-07	1.969E-07	1.969E-07	1.969E-07	1.979E-07	1.968E-07	1.969E-07	1.968E-07	1.969E-07	1.966E-07	1.968E-07	1.969E-07	0.15
8 000	3.116E-07	3.118E-07	3.118E-07	3.115E-07	3.115E-07	3.115E-07	3.115E-07	3.115E-07	3.132E-07	3.114E-07	3.115E-07	3.114E-07	3.115E-07	3.110E-07	3.115E-07	3.116E-07	0.16
10 000	3.858E-07	3.860E-07	3.860E-07	3.857E-07	3.857E-07	3.857E-07	3.857E-07	3.857E-07	3.878E-07	3.855E-07	3.857E-07	3.856E-07	3.855E-07	3.850E-07	3.857E-07	3.858E-07	0.16
15 000	5.636E-07	5.640E-07	5.639E-07	5.636E-07	5.635E-07	5.635E-07	5.635E-07	5.635E-07	5.669E-07	5.633E-07	5.635E-07	5.634E-07	5.634E-07	5.621E-07	5.635E-07	5.637E-07	0.18
20 000	7.310E-07	7.315E-07	7.314E-07	7.309E-07	7.308E-07	7.308E-07	7.308E-07	7.308E-07	7.356E-07	7.334E-07	7.308E-07	7.307E-07	7.307E-07	7.286E-07	7.308E-07	7.312E-07	0.22
25 000	8.883E-07	8.889E-07	8.889E-07	8.883E-07	8.881E-07	8.882E-07	8.882E-07	8.882E-07	8.944E-07	8.905E-07	8.882E-07	8.880E-07	8.881E-07	8.849E-07	8.882E-07	8.886E-07	0.23
30 000	1.036E-06	1.037E-06	1.037E-06	1.036E-06	1.036E-06	1.036E-06	1.036E-06	1.036E-06	1.044E-06	1.038E-06	1.036E-06	1.036E-06	1.036E-06	1.032E-06	1.036E-06	1.036E-06	0.24
40 000	1.305E-06	1.306E-06	1.306E-06	1.305E-06	1.305E-06	1.305E-06	1.305E-06	1.305E-06	1.316E-06	1.307E-06	1.305E-06	1.305E-06	1.305E-06	1.298E-06	1.305E-06	1.305E-06	0.28
45 000	1.427E-06	1.428E-06	1.428E-06	1.427E-06	1.427E-06	1.427E-06	1.427E-06	1.427E-06	1.439E-06	1.429E-06	1.427E-06	1.427E-06	1.427E-06	1.418E-06	1.427E-06	1.427E-06	0.30
50 000	1.542E-06	1.543E-06	1.542E-06	1.541E-06	1.541E-06	1.541E-06	1.541E-06	1.541E-06	1.555E-06	1.543E-06	1.541E-06	1.541E-06	1.541E-06	1.531E-06	1.541E-06	1.542E-06	0.32
100 000	2.332E-06	2.333E-06	2.333E-06	2.332E-06	2.332E-06	2.332E-06	2.332E-06	2.332E-06	2.361E-06	2.332E-06	2.332E-06	2.331E-06	2.331E-06	2.299E-06	2.332E-06	2.332E-06	0.53
500 000	1.756E-06	1.755E-06	1.755E-06	1.755E-06	1.756E-06	1.756E-06	1.756E-06	1.756E-06	1.801E-06	1.757E-06	1.755E-06	1.755E-06	1.755E-06	1.547E-06	1.755E-06	1.745E-06	3.32
1 000 000	7.234E-07	7.228E-07	7.229E-07	7.233E-07	7.233E-07	7.233E-07	7.235E-07	7.235E-07	7.399E-07	7.240E-07	7.232E-07	7.231E-07	7.233E-07	3.983E-07	7.232E-07	7.027E-07	12.42

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 36. Relative difference from sample mean as a function of decay time for ^{230}Th atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 57. ^{230}Th half-life and associated uncertainty values

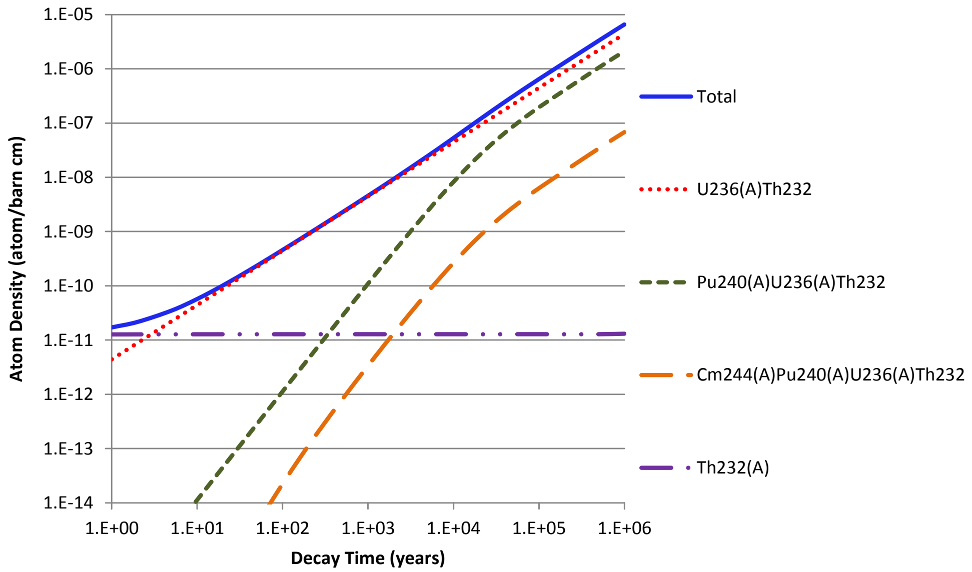
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.37881E+12	2.37876E+12	2.37944E+12	2.37939E+12	2.37881E+12	2.43000E+12
Uncertainty (s)	9.46728E+09	9.46708E+09	9.46728E+09	-	9.46726E+08	-

Sources: References 12–14, 20 and 21.

3.29. Time-dependent ^{232}Th atom densities

^{232}Th is an actinide important for radiological dose assessments. This nuclide has a half-life of $1.405\times10^{10} \pm 6\times10^{7}$ years and decays by alpha-particle emission [20]. ^{232}Th concentrations increase after fuel discharge predominantly due to the ^{236}U alpha decay. The cumulative ^{232}Th atom density and individual contributions from decay chains forming ^{232}Th are shown as a function of decay time in Figure 37.

Figure 37. ^{232}Th atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 58. In the table, the calculated ^{232}Th atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{232}Th using the evaluated decay codes/data libraries is illustrated in Figure 38. There is a very small dispersion of the results (RSD ≈ 0.3%) that may be attributed to the different ^{236}U half-life values used. The ^{232}Th and ^{236}U half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 59 and Table 71, respectively.

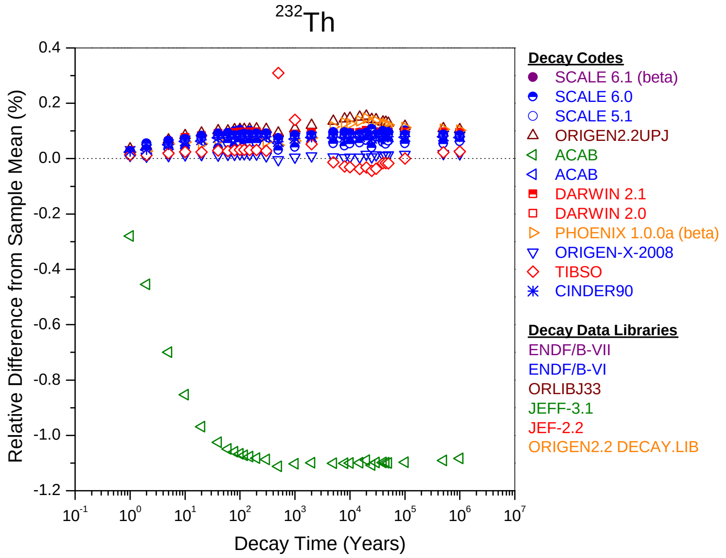
Table 58. Decay calculation results for ^{232}Th (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	1.269E-11	0.00
1	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.709E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	1.714E-11	0.08
2	2.159E-11	2.160E-11	2.160E-11	2.160E-11	2.160E-11	2.149E-11	2.160E-11	2.160E-11	2.159E-11	2.159E-11	2.160E-11	2.159E-11	2.160E-11	2.159E-11	2.160E-11	2.159E-11	0.13
5	3.495E-11	3.496E-11	3.496E-11	3.496E-11	3.496E-11	3.469E-11	3.496E-11	3.496E-11	3.496E-11	3.494E-11	3.496E-11	3.495E-11	3.496E-11	3.494E-11	3.495E-11	3.494E-11	0.19
10	5.723E-11	5.723E-11	5.724E-11	5.723E-11	5.723E-11	5.670E-11	5.723E-11	5.723E-11	5.722E-11	5.720E-11	5.723E-11	5.721E-11	5.723E-11	5.720E-11	5.723E-11	5.719E-11	0.24
20	1.018E-10	1.018E-10	1.018E-10	1.018E-10	1.018E-10	1.007E-10	1.018E-10	1.018E-10	1.018E-10	1.017E-10	1.018E-10	1.018E-10	1.018E-10	1.017E-10	1.018E-10	1.017E-10	0.27
40	1.910E-10	1.910E-10	1.910E-10	1.910E-10	1.910E-10	1.889E-10	1.910E-10	1.910E-10	1.910E-10	1.909E-10	1.910E-10	1.909E-10	1.910E-10	1.909E-10	1.910E-10	1.908E-10	0.28
60	2.803E-10	2.803E-10	2.803E-10	2.803E-10	2.803E-10	2.771E-10	2.803E-10	2.803E-10	2.802E-10	2.801E-10	2.803E-10	2.802E-10	2.803E-10	2.801E-10	2.803E-10	2.800E-10	0.29
80	3.697E-10	3.697E-10	3.697E-10	3.697E-10	3.696E-10	3.654E-10	3.697E-10	3.697E-10	3.696E-10	3.694E-10	3.696E-10	3.695E-10	3.696E-10	3.694E-10	3.696E-10	3.693E-10	0.29
100	4.591E-10	4.591E-10	4.592E-10	4.592E-10	4.591E-10	4.538E-10	4.592E-10	4.592E-10	4.590E-10	4.588E-10	4.591E-10	4.590E-10	4.591E-10	4.589E-10	4.591E-10	4.587E-10	0.30
120	5.487E-10	5.487E-10	5.488E-10	5.487E-10	5.486E-10	5.423E-10	5.487E-10	5.487E-10	5.486E-10	5.483E-10	5.487E-10	5.485E-10	5.487E-10	5.484E-10	5.487E-10	5.482E-10	0.30
150	6.832E-10	6.832E-10	6.833E-10	6.833E-10	6.832E-10	6.753E-10	6.833E-10	6.833E-10	6.831E-10	6.827E-10	6.832E-10	6.830E-10	6.832E-10	6.828E-10	6.832E-10	6.826E-10	0.30
200	9.079E-10	9.079E-10	9.081E-10	9.079E-10	9.078E-10	8.973E-10	9.080E-10	9.080E-10	9.077E-10	9.072E-10	9.079E-10	9.076E-10	9.079E-10	9.074E-10	9.078E-10	9.071E-10	0.30
300	1.359E-09	1.359E-09	1.359E-09	1.359E-09	1.359E-09	1.343E-09	1.359E-09	1.359E-09	1.359E-09	1.358E-09	1.359E-09	1.359E-09	1.359E-09	1.358E-09	1.359E-09	1.358E-09	0.30
500	2.268E-09	2.268E-09	2.268E-09	2.268E-09	2.268E-09	2.241E-09	2.268E-09	2.268E-09	2.267E-09	2.266E-09	2.268E-09	2.267E-09	2.268E-09	2.273E-09	2.268E-09	2.266E-09	0.31
1 000	4.579E-09	4.579E-09	4.580E-09	4.579E-09	4.578E-09	4.525E-09	4.579E-09	4.579E-09	4.578E-09	4.575E-09	4.579E-09	4.577E-09	4.579E-09	4.581E-09	4.578E-09	4.575E-09	0.31
2 000	9.357E-09	9.356E-09	9.360E-09	9.357E-09	9.356E-09	9.246E-09	9.357E-09	9.357E-09	9.356E-09	9.349E-09	9.356E-09	9.354E-09	9.356E-09	9.353E-09	9.356E-09	9.348E-09	0.30
5 000	2.476E-08	2.476E-08	2.477E-08	2.476E-08	2.476E-08	2.446E-08	2.476E-08	2.476E-08	2.477E-08	2.474E-08	2.476E-08	2.475E-08	2.476E-08	2.473E-08	2.476E-08	2.474E-08	0.31
8 000	4.142E-08	4.142E-08	4.144E-08	4.142E-08	4.141E-08	4.093E-08	4.142E-08	4.142E-08	4.143E-08	4.138E-08	4.142E-08	4.140E-08	4.142E-08	4.137E-08	4.141E-08	4.138E-08	0.31
10 000	5.305E-08	5.305E-08	5.308E-08	5.305E-08	5.304E-08	5.242E-08	5.305E-08	5.305E-08	5.307E-08	5.300E-08	5.305E-08	5.303E-08	5.305E-08	5.298E-08	5.304E-08	5.300E-08	0.31
15 000	8.342E-08	8.342E-08	8.348E-08	8.343E-08	8.342E-08	8.244E-08	8.343E-08	8.343E-08	8.347E-08	8.336E-08	8.342E-08	8.340E-08	8.342E-08	8.332E-08	8.342E-08	8.335E-08	0.31
20 000	1.150E-07	1.150E-07	1.151E-07	1.150E-07	1.150E-07	1.137E-07	1.150E-07	1.150E-07	1.151E-07	1.149E-07	1.150E-07	1.150E-07	1.150E-07	1.149E-07	1.150E-07	1.149E-07	0.31
25 000	1.474E-07	1.474E-07	1.474E-07	1.474E-07	1.474E-07	1.456E-07	1.474E-07	1.474E-07	1.474E-07	1.473E-07	1.474E-07	1.473E-07	1.474E-07	1.472E-07	1.473E-07	1.472E-07	0.31
30 000	1.801E-07	1.801E-07	1.802E-07	1.801E-07	1.801E-07	1.780E-07	1.801E-07	1.801E-07	1.802E-07	1.800E-07	1.801E-07	1.801E-07	1.801E-07	1.799E-07	1.801E-07	1.800E-07	0.31
40 000	2.462E-07	2.463E-07	2.464E-07	2.463E-07	2.462E-07	2.434E-07	2.463E-07	2.463E-07	2.464E-07	2.461E-07	2.463E-07	2.462E-07	2.463E-07	2.460E-07	2.462E-07	2.461E-07	0.31
45 000	2.795E-07	2.795E-07	2.796E-07	2.795E-07	2.795E-07	2.762E-07	2.795E-07	2.795E-07	2.796E-07	2.793E-07	2.795E-07	2.794E-07	2.795E-07	2.792E-07	2.795E-07	2.793E-07	0.31
50 000	3.127E-07	3.128E-07	3.129E-07	3.128E-07	3.127E-07	3.091E-07	3.128E-07	3.128E-07	3.129E-07	3.125E-07	3.128E-07	3.127E-07	3.128E-07	3.124E-07	3.127E-07	3.125E-07	0.31
100 000	6.459E-07	6.459E-07	6.461E-07	6.460E-07	6.458E-07	6.383E-07	6.460E-07	6.460E-07	6.461E-07	6.454E-07	6.459E-07	6.457E-07	6.459E-07	6.453E-07	6.459E-07	6.453E-07	0.31
500 000	3.294E-06	3.294E-06	3.295E-06	3.294E-06	3.294E-06	3.255E-06	3.294E-06	3.294E-06	3.295E-06	3.292E-06	3.294E-06	3.293E-06	3.294E-06	3.292E-06	3.294E-06	3.291E-06	0.30
1 000 000	6.560E-06	6.561E-06	6.562E-06	6.561E-06	6.560E-06	6.484E-06	6.561E-06	6.561E-06	6.562E-06	6.556E-06	6.560E-06	6.559E-06	6.560E-06	6.557E-06	6.560E-06	6.555E-06	0.30

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 38. Relative difference from sample mean as a function of decay time for ^{232}Th atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 59. ^{232}Th half-life and associated uncertainty values

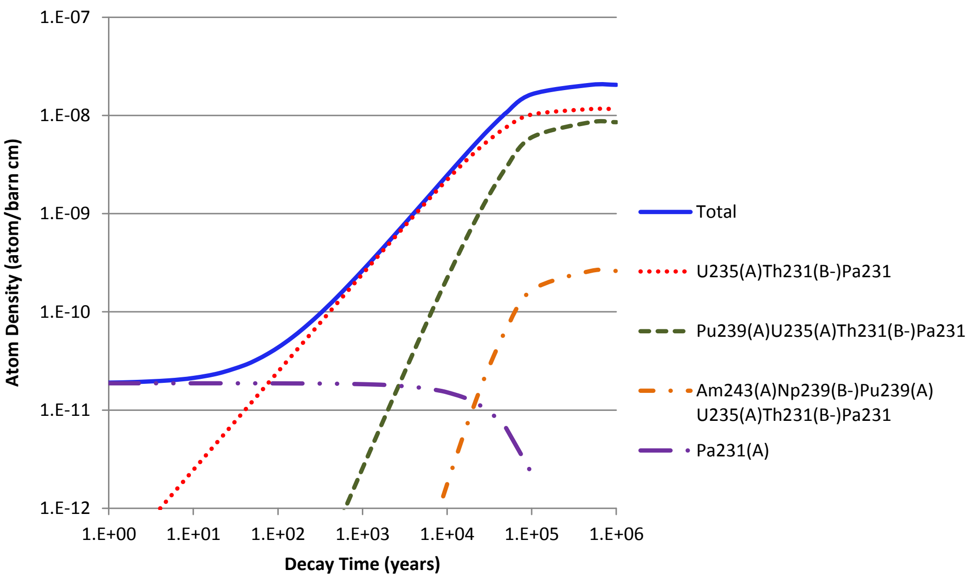
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	4.43384E+17	4.43375E+17	4.43384E+17	4.41797E+17	4.43400E+17
Uncertainty (s)	1.89345E+15	1.89342E+15	1.89346E+15	-	-

Sources: References 12, 13, 20 and 21.

3.30. Time-dependent ^{231}Pa atom densities

^{231}Pa is an actinide important for radiological dose assessments. This nuclide has a half-life of $3.276\times10^4 \pm 110$ years and decays by alpha-particle emission [20]. ^{231}Pa atom density continuously increases after fuel discharge primarily due to ^{235}U alpha decay to the short-lived nuclide ^{231}Th ($T_{1/2}$ = 25.52 hours), which undergoes beta decay forming ^{231}Pa. The cumulative ^{231}Pa atom density and individual contributions from decay chains forming ^{231}Pa are shown as a function of decay time in Figure 39.

Figure 39. ^{231}Pa atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 60. In the table, the calculated ^{231}Pa atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{231}Pa using the evaluated decay codes/data libraries is illustrated in Figure 40. As seen in the figure, the dispersion of the ^{231}Pa atom density results is insignificant at any given decay time. The ^{231}Pa half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 61.

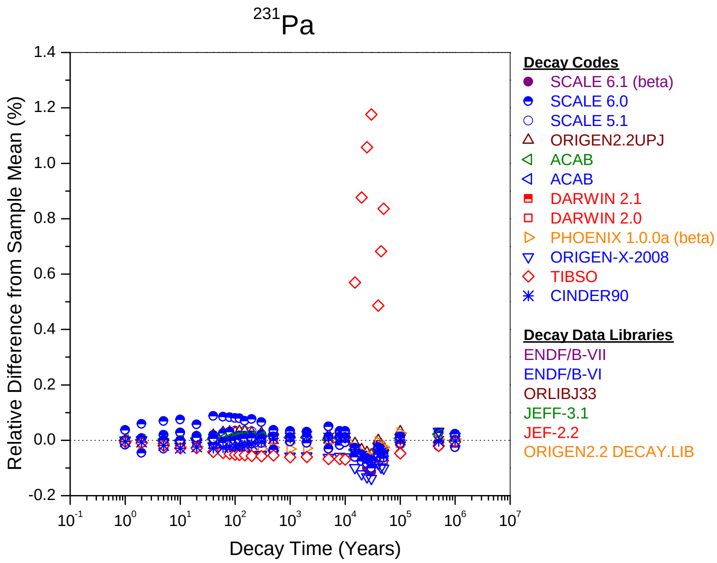
Table 60. Decay calculation results for ^{231}Pa (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	1.874E-11	0.00
1	1.904E-11	1.904E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	1.904E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	1.903E-11	0.02
2	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	1.929E-11	1.927E-11	1.928E-11	1.928E-11	1.928E-11	1.928E-11	0.02
5	2.002E-11	2.002E-11	2.002E-11	2.002E-11	2.002E-11	2.002E-11	2.001E-11	2.001E-11	2.001E-11	2.002E-11	2.003E-11	2.001E-11	2.002E-11	2.001E-11	2.001E-11	2.002E-11	0.02
10	2.125E-11	2.125E-11	2.124E-11	2.125E-11	2.124E-11	2.124E-11	2.124E-11	2.124E-11	2.124E-11	2.124E-11	2.126E-11	2.124E-11	2.124E-11	2.124E-11	2.124E-11	2.124E-11	0.03
20	2.370E-11	2.370E-11	2.370E-11	2.370E-11	2.370E-11	2.370E-11	2.369E-11	2.369E-11	2.369E-11	2.370E-11	2.371E-11	2.369E-11	2.370E-11	2.369E-11	2.369E-11	2.370E-11	0.02
40	2.861E-11	2.861E-11	2.861E-11	2.861E-11	2.861E-11	2.861E-11	2.860E-11	2.860E-11	2.860E-11	2.860E-11	2.863E-11	2.860E-11	2.861E-11	2.859E-11	2.860E-11	2.860E-11	0.03
60	3.352E-11	3.352E-11	3.352E-11	3.352E-11	3.351E-11	3.351E-11	3.351E-11	3.351E-11	3.350E-11	3.350E-11	3.354E-11	3.351E-11	3.351E-11	3.350E-11	3.350E-11	3.351E-11	0.03
80	3.843E-11	3.843E-11	3.843E-11	3.843E-11	3.842E-11	3.842E-11	3.841E-11	3.841E-11	3.841E-11	3.841E-11	3.845E-11	3.841E-11	3.842E-11	3.840E-11	3.841E-11	3.842E-11	0.03
100	4.334E-11	4.333E-11	4.334E-11	4.333E-11	4.333E-11	4.333E-11	4.332E-11	4.332E-11	4.331E-11	4.331E-11	4.336E-11	4.332E-11	4.332E-11	4.330E-11	4.332E-11	4.333E-11	0.03
120	4.824E-11	4.824E-11	4.825E-11	4.824E-11	4.824E-11	4.824E-11	4.823E-11	4.823E-11	4.821E-11	4.822E-11	4.827E-11	4.823E-11	4.823E-11	4.821E-11	4.822E-11	4.823E-11	0.03
150	5.561E-11	5.560E-11	5.561E-11	5.560E-11	5.560E-11	5.560E-11	5.559E-11	5.559E-11	5.557E-11	5.556E-11	5.563E-11	5.559E-11	5.559E-11	5.556E-11	5.558E-11	5.559E-11	0.03
200	6.788E-11	6.787E-11	6.788E-11	6.787E-11	6.787E-11	6.787E-11	6.785E-11	6.785E-11	6.784E-11	6.782E-11	6.791E-11	6.785E-11	6.786E-11	6.782E-11	6.785E-11	6.786E-11	0.03
300	9.241E-11	9.241E-11	9.241E-11	9.241E-11	9.240E-11	9.240E-11	9.239E-11	9.239E-11	9.236E-11	9.234E-11	9.245E-11	9.238E-11	9.239E-11	9.234E-11	9.238E-11	9.239E-11	0.03
500	1.415E-10	1.415E-10	1.415E-10	1.415E-10	1.415E-10	1.415E-10	1.415E-10	1.415E-10	1.414E-10	1.414E-10	1.415E-10	1.414E-10	1.415E-10	1.414E-10	1.415E-10	1.415E-10	0.03
1 000	2.642E-10	2.642E-10	2.642E-10	2.642E-10	2.641E-10	2.641E-10	2.641E-10	2.641E-10	2.640E-10	2.640E-10	2.642E-10	2.641E-10	2.641E-10	2.640E-10	2.641E-10	2.641E-10	0.03
2 000	5.095E-10	5.094E-10	5.094E-10	5.095E-10	5.094E-10	5.094E-10	5.094E-10	5.094E-10	5.092E-10	5.091E-10	5.095E-10	5.093E-10	5.094E-10	5.090E-10	5.094E-10	5.094E-10	0.03
5 000	1.244E-09	1.244E-09	1.244E-09	1.244E-09	1.243E-09	1.243E-09	1.243E-09	1.243E-09	1.243E-09	1.243E-09	1.244E-09	1.243E-09	1.244E-09	1.243E-09	1.243E-09	1.243E-09	0.04
8 000	1.973E-09	1.973E-09	1.973E-09	1.973E-09	1.973E-09	1.973E-09	1.972E-09	1.972E-09	1.973E-09	1.971E-09	1.973E-09	1.972E-09	1.973E-09	1.971E-09	1.973E-09	1.972E-09	0.03
10 000	2.455E-09	2.455E-09	2.455E-09	2.455E-09	2.454E-09	2.454E-09	2.454E-09	2.454E-09	2.454E-09	2.453E-09	2.455E-09	2.454E-09	2.454E-09	2.452E-09	2.454E-09	2.454E-09	0.03
15 000	3.639E-09	3.639E-09	3.640E-09	3.639E-09	3.639E-09	3.639E-09	3.639E-09	3.639E-09	3.639E-09	3.637E-09	3.639E-09	3.638E-09	3.639E-09	3.661E-09	3.639E-09	3.640E-09	0.16
20 000	4.788E-09	4.788E-09	4.789E-09	4.788E-09	4.788E-09	4.788E-09	4.787E-09	4.787E-09	4.789E-09	4.785E-09	4.788E-09	4.787E-09	4.788E-09	4.833E-09	4.788E-09	4.791E-09	0.24
25 000	5.894E-09	5.894E-09	5.895E-09	5.894E-09	5.894E-09	5.894E-09	5.893E-09	5.893E-09	5.895E-09	5.890E-09	5.894E-09	5.893E-09	5.894E-09	5.960E-09	5.894E-09	5.898E-09	0.29
30 000	6.952E-09	6.952E-09	6.953E-09	6.952E-09	6.951E-09	6.951E-09	6.951E-09	6.951E-09	6.953E-09	6.947E-09	6.952E-09	6.950E-09	6.952E-09	7.039E-09	6.951E-09	6.957E-09	0.33
40 000	8.910E-09	8.910E-09	8.912E-09	8.911E-09	8.910E-09	8.910E-09	8.909E-09	8.909E-09	8.912E-09	8.905E-09	8.910E-09	8.908E-09	8.910E-09	8.956E-09	8.910E-09	8.913E-09	0.14
45 000	9.808E-09	9.808E-09	9.811E-09	9.809E-09	9.808E-09	9.807E-09	9.806E-09	9.806E-09	9.810E-09	9.803E-09	9.808E-09	9.806E-09	9.808E-09	9.879E-09	9.807E-09	9.812E-09	0.19
50 000	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.065E-08	1.075E-08	1.065E-08	1.066E-08	0.23
100 000	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.643E-08	1.642E-08	1.643E-08	1.643E-08	0.02
500 000	2.050E-08	2.050E-08	2.049E-08	2.050E-08	2.050E-08	2.050E-08	2.049E-08	2.049E-08	2.050E-08	2.050E-08	2.049E-08	2.049E-08	2.049E-08	2.049E-08	2.049E-08	2.050E-08	0.02
1 000 000	2.049E-08	2.049E-08	2.049E-08	2.049E-08	2.049E-08	2.049E-08	2.048E-08	2.048E-08	2.049E-08	2.049E-08	2.049E-08	2.048E-08	2.049E-08	2.048E-08	2.048E-08	2.049E-08	0.01

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 40. Relative difference from sample mean as a function of decay time for ^{231}Pa atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 61. ^{231}Pa half-life and associated uncertainty values

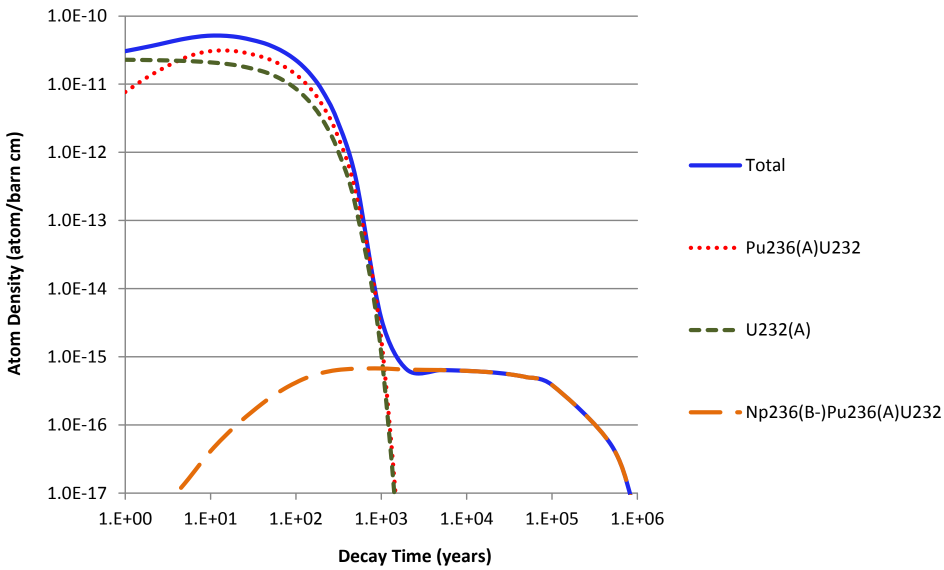
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.03382E+12	1.03380E+12	1.03383E+12	1.03507E+12	1.03400E+12
Uncertainty (s)	3.47134E+09	3.47126E+09	3.47134E+09	-	-

Sources: References 12, 13, 20 and 21.

3.31. Time-dependent ^{232}U atom densities

^{232}U is an actinide nuclide important for radiological dose assessments. This nuclide has a half-life of 68.9 ± 0.4 years and decays by alpha-particle emission and spontaneous fission [20]. ^{236}Pu ($T_{1/2}$ = 2.858 ± 0.008 years) alpha decay contributes to the formation of the ^{232}U nuclide for approximately 10^3 years following fuel discharge; the ^{232}U quantities after $2{\times}10^3$ years are exclusively produced by ^{236}Np beta decay. The cumulative ^{232}U atom density and individual contributions from significant decay chains forming ^{232}U are shown as a function of decay time in Figure 41.

Figure 41. ^{232}U atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5-wt% ^{235}U initial enrichment and 50-GWd/MTU burn-up;
A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 62. In the table, the calculated ^{232}U atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{232}U using the evaluated decay codes/data libraries is illustrated in Figure 42. The dispersion of the results (RSD ≈ 10%) observed at approximately 10^3 years may be attributed to the different ^{232}U and ^{236}Pu half-life values used by the decay codes; the large dispersion (RSD ≈ 70%) of the ^{232}U atom density results at 10^6 years may be attributed to the different ^{236}Np half-life and branching ratio values used by the evaluated codes. The ^{232}U, ^{236}Pu, and ^{236}Np half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 63. The values of the ^{236}Np branching ratio for beta decay associated with those libraries are also presented in the table.

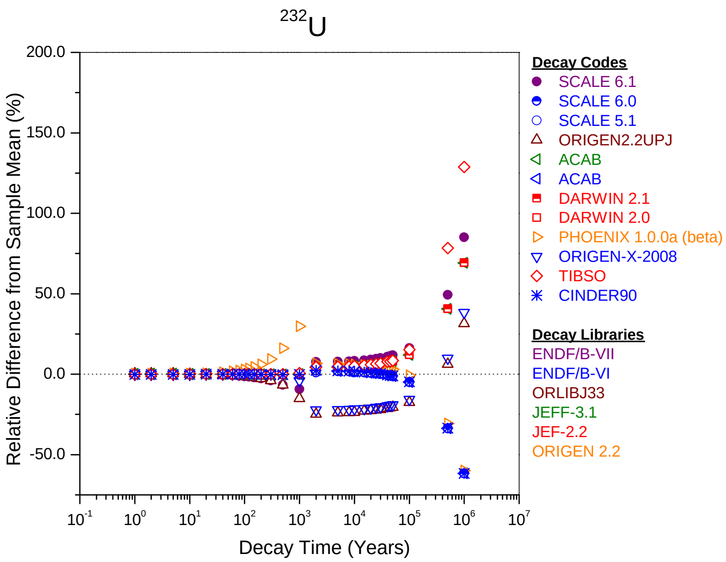
Table 62. Decay calculation results for ^{232}U (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	2.311E-11	0.00
1	3.050E-11	3.060E-11	3.062E-11	3.051E-11	3.050E-11	3.060E-11	3.050E-11	3.050E-11	3.062E-11	3.050E-11	3.050E-11	3.050E-11	3.050E-11	3.050E-11	3.050E-11	3.053E-11	0.17
2	3.620E-11	3.635E-11	3.638E-11	3.621E-11	3.621E-11	3.636E-11	3.621E-11	3.621E-11	3.640E-11	3.620E-11	3.621E-11	3.620E-11	3.621E-11	3.620E-11	3.621E-11	3.625E-11	0.22
5	4.639E-11	4.656E-11	4.659E-11	4.640E-11	4.640E-11	4.658E-11	4.640E-11	4.640E-11	4.666E-11	4.639E-11	4.640E-11	4.638E-11	4.640E-11	4.639E-11	4.640E-11	4.645E-11	0.21
10	5.153E-11	5.158E-11	5.160E-11	5.154E-11	5.154E-11	5.164E-11	5.154E-11	5.154E-11	5.178E-11	5.154E-11	5.154E-11	5.152E-11	5.154E-11	5.154E-11	5.154E-11	5.157E-11	0.13
20	4.947E-11	4.936E-11	4.936E-11	4.947E-11	4.947E-11	4.948E-11	4.948E-11	4.948E-11	4.974E-11	4.948E-11	4.947E-11	4.946E-11	4.947E-11	4.949E-11	4.947E-11	4.948E-11	0.17
40	4.081E-11	4.060E-11	4.060E-11	4.082E-11	4.082E-11	4.081E-11	4.082E-11	4.082E-11	4.127E-11	4.083E-11	4.082E-11	4.080E-11	4.082E-11	4.084E-11	4.082E-11	4.082E-11	0.37
60	3.346E-11	3.320E-11	3.320E-11	3.347E-11	3.347E-11	3.346E-11	3.347E-11	3.347E-11	3.404E-11	3.348E-11	3.347E-11	3.346E-11	3.347E-11	3.349E-11	3.347E-11	3.347E-11	0.57
80	2.744E-11	2.715E-11	2.715E-11	2.744E-11	2.744E-11	2.743E-11	2.744E-11	2.744E-11	2.808E-11	2.746E-11	2.744E-11	2.743E-11	2.744E-11	2.746E-11	2.744E-11	2.745E-11	0.77
100	2.250E-11	2.220E-11	2.220E-11	2.250E-11	2.250E-11	2.249E-11	2.250E-11	2.250E-11	2.317E-11	2.251E-11	2.250E-11	2.249E-11	2.250E-11	2.252E-11	2.250E-11	2.250E-11	0.97
120	1.844E-11	1.816E-11	1.816E-11	1.845E-11	1.845E-11	1.844E-11	1.845E-11	1.845E-11	1.911E-11	1.846E-11	1.844E-11	1.844E-11	1.844E-11	1.846E-11	1.844E-11	1.845E-11	1.17
150	1.369E-11	1.343E-11	1.343E-11	1.369E-11	1.369E-11	1.369E-11	1.369E-11	1.369E-11	1.432E-11	1.371E-11	1.369E-11	1.369E-11	1.369E-11	1.371E-11	1.369E-11	1.370E-11	1.48
200	8.334E-12	8.118E-12	8.119E-12	8.335E-12	8.336E-12	8.333E-12	8.335E-12	8.335E-12	8.850E-12	8.347E-12	8.334E-12	8.332E-12	8.334E-12	8.347E-12	8.334E-12	8.342E-12	1.99
300	3.088E-12	2.969E-12	2.969E-12	3.088E-12	3.089E-12	3.088E-12	3.088E-12	3.088E-12	3.381E-12	3.095E-12	3.088E-12	3.087E-12	3.088E-12	3.095E-12	3.088E-12	3.093E-12	3.03
500	4.244E-13	3.975E-13	3.975E-13	4.244E-13	4.246E-13	4.244E-13	4.244E-13	4.244E-13	4.940E-13	4.258E-13	4.244E-13	4.243E-13	4.244E-13	4.258E-13	4.243E-13	4.256E-13	5.16
1 000	3.619E-15	3.289E-15	3.086E-15	3.619E-15	3.621E-15	3.632E-15	3.636E-15	3.636E-15	4.708E-15	3.482E-15	3.614E-15	3.618E-15	3.619E-15	3.656E-15	3.624E-15	3.631E-15	9.66
2 000	6.633E-16	6.977E-16	4.880E-16	6.633E-16	6.633E-16	6.763E-16	6.768E-16	6.768E-16	6.923E-16	5.048E-16	6.552E-16	6.631E-16	6.633E-16	6.769E-16	6.642E-16	6.483E-16	10.04
5 000	6.513E-16	6.882E-16	4.854E-16	6.513E-16	6.512E-16	6.669E-16	6.674E-16	6.674E-16	6.796E-16	4.979E-16	6.516E-16	6.510E-16	6.512E-16	6.683E-16	6.522E-16	6.387E-16	9.88
8 000	6.396E-16	6.790E-16	4.789E-16	6.396E-16	6.396E-16	6.579E-16	6.584E-16	6.584E-16	6.674E-16	4.912E-16	6.399E-16	6.394E-16	6.396E-16	6.592E-16	6.405E-16	6.286E-16	9.83
10 000	6.319E-16	6.729E-16	4.746E-16	6.319E-16	6.319E-16	6.519E-16	6.524E-16	6.524E-16	6.594E-16	4.869E-16	6.272E-16	6.317E-16	6.319E-16	6.529E-16	6.328E-16	6.215E-16	9.79
15 000	6.132E-16	6.579E-16	4.676E-16	6.132E-16	6.131E-16	6.372E-16	6.377E-16	6.377E-16	6.399E-16	4.761E-16	6.131E-16	6.130E-16	6.131E-16	6.392E-16	6.140E-16	6.057E-16	9.63
20 000	5.950E-16	6.433E-16	4.572E-16	5.950E-16	5.949E-16	6.228E-16	6.233E-16	6.233E-16	6.209E-16	4.656E-16	5.949E-16	5.948E-16	5.949E-16	6.248E-16	5.958E-16	5.898E-16	9.59
25 000	5.773E-16	6.289E-16	4.470E-16	5.773E-16	5.773E-16	6.088E-16	6.093E-16	6.093E-16	6.024E-16	4.553E-16	5.773E-16	5.771E-16	5.773E-16	6.108E-16	5.781E-16	5.742E-16	9.56
30 000	5.602E-16	6.150E-16	4.370E-16	5.602E-16	5.601E-16	5.951E-16	5.955E-16	5.955E-16	5.845E-16	4.452E-16	5.601E-16	5.600E-16	5.601E-16	5.970E-16	5.610E-16	5.591E-16	9.55
40 000	5.274E-16	5.879E-16	4.178E-16	5.274E-16	5.274E-16	5.685E-16	5.690E-16	5.690E-16	5.504E-16	4.258E-16	5.274E-16	5.272E-16	5.274E-16	5.720E-16	5.281E-16	5.302E-16	9.58
45 000	5.117E-16	5.748E-16	4.085E-16	5.117E-16	5.117E-16	5.557E-16	5.562E-16	5.562E-16	5.340E-16	4.164E-16	5.117E-16	5.116E-16	5.117E-16	5.576E-16	5.125E-16	5.161E-16	9.60
50 000	4.965E-16	5.620E-16	3.994E-16	4.965E-16	4.965E-16	5.432E-16	5.436E-16	5.436E-16	5.182E-16	4.072E-16	4.965E-16	4.964E-16	4.965E-16	5.450E-16	4.973E-16	5.026E-16	9.65
100 000	3.673E-16	4.487E-16	3.189E-16	3.673E-16	3.673E-16	4.325E-16	4.328E-16	4.328E-16	3.833E-16	3.256E-16	3.673E-16	3.672E-16	3.673E-16	4.453E-16	3.679E-16	3.861E-16	11.18
500 000	3.295E-17	7.413E-17	5.270E-17	3.295E-17	3.296E-17	6.979E-17	6.984E-17	6.984E-17	3.440E-17	5.450E-17	3.295E-17	3.294E-17	3.295E-17	8.857E-17	3.301E-17	4.963E-17	40.51
1 000 000	1.618E-18	7.808E-18	5.551E-18	1.618E-18	1.618E-18	7.139E-18	7.143E-18	7.143E-18	1.689E-18	5.834E-18	1.618E-18	1.617E-18	1.618E-18	9.651E-18	1.621E-18	4.219E-18	71.68

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 42. Relative difference from sample mean as a function of decay time for ^{232}U atom density



1. Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.
2. Small deviations might occur in the ORIGEN-X-2008 calculated concentrations for times beyond 150 years due to a splitting of the calculation and due to the choice of large time steps.

Table 63. ^{232}U, ^{236}Pu, and ^{236}Np decay data

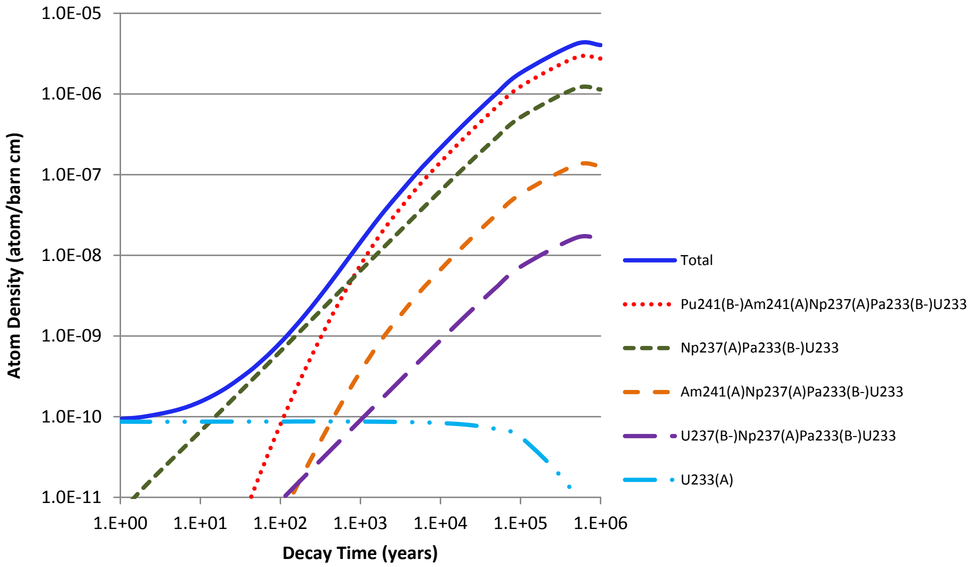
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.17432E+09	2.20267E+09	2.20272E+09	2.20267E+09	2.17431E+09	2.27200E+09
Uncertainty (s)	1.26230E+07	1.57785E+07	1.57788E+07	-	1.26230E+07	-
		^{236}Pu				
Half-life (s)	9.01916E+07	9.15151E+07	9.01916E+07	9.15151E+07	9.01915E+07	8.99700E+07
Uncertainty (s)	2.52461E+05	3.15569E+06	1.89346E+05	-	2.52460E+05	-
		^{236}Np				
Half-life (s)	4.85987E+12	3.62905E+12	4.79675E+12	4.79665E+12	4.85986E+12	3.62900E+12
Uncertainty (s)	1.89345E+11	3.78683E+11	9.46728E+10	-	1.89345E+11	-
^{236}Np branching ratio for beta decay	1.25050E-01	8.89999E-02	1.18000E-01	1.18050E-01	1.25000E-01	9.00000E-02

Sources: References 12–14, 20 and 21.

3.32. Time-dependent ^{233}U atom densities

^{233}U is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $1.592 \times 10^5 \pm 200$ years and decays by alpha-particle emission and spontaneous fission [20]. ^{233}U concentrations continuously increase after fuel discharge as a result of a series of decay chains, the most predominant chains being $^{241}Pu(\beta^-)^{214}Am(\alpha)^{237}Np(\alpha)^{233}Pa(\beta^-)^{233}U$ and $^{237}Np(\alpha)^{233}Pa(\beta^-)^{233}U$. The cumulative ^{233}U atom density and individual contributions from decay chains forming ^{233}U are shown as a function of decay time in Figure 43.

Figure 43. ^{233}U atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

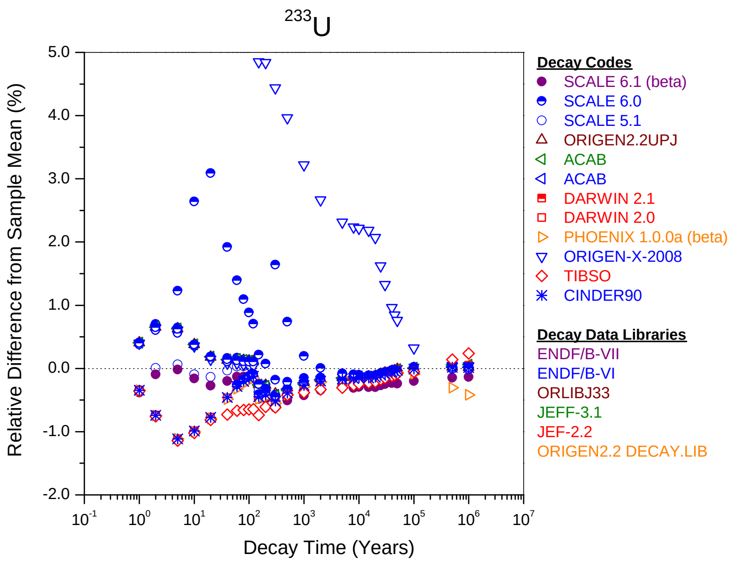
The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 64. In the table, the calculated ^{233}U atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{233}U using the evaluated decay codes/data libraries is illustrated in Figure 44. A small dispersion of the ^{233}U atom density results (RSD ~ 1%), possibly related to numerical approximations, is observed for the first 100 years after fuel discharge. Small deviations occurred in the ^{233}U atom densities calculated with ORIGEN-X-2008 for decay times greater than 150 years due to calculation approximations (see Appendix B). The ^{233}U half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 65.

Table 64. Decay calculation results for ^{233}U (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	8.708E-11	0.00
1	9.292E-11	9.288E-11	9.362E-11	9.362E-11	9.362E-11	9.362E-11	9.292E-11	9.292E-11	9.291E-11	9.361E-11	9.291E-11	9.359E-11	9.361E-11	9.290E-11	9.292E-11	9.324E-11	0.39
2	1.002E-10	1.001E-10	1.009E-10	1.009E-10	1.009E-10	1.009E-10	9.945E-11	9.945E-11	9.945E-11	1.008E-10	9.945E-11	1.008E-10	1.008E-10	9.943E-11	9.945E-11	1.002E-10	0.67
5	1.205E-10	1.204E-10	1.212E-10	1.212E-10	1.212E-10	1.212E-10	1.191E-10	1.191E-10	1.191E-10	1.212E-10	1.219E-10	1.211E-10	1.212E-10	1.190E-10	1.191E-10	1.204E-10	0.86
10	1.533E-10	1.532E-10	1.540E-10	1.540E-10	1.540E-10	1.540E-10	1.519E-10	1.519E-10	1.519E-10	1.540E-10	1.575E-10	1.540E-10	1.540E-10	1.519E-10	1.519E-10	1.534E-10	0.96
20	2.199E-10	2.196E-10	2.206E-10	2.206E-10	2.206E-10	2.206E-10	2.185E-10	2.185E-10	2.185E-10	2.205E-10	2.270E-10	2.206E-10	2.206E-10	2.184E-10	2.185E-10	2.202E-10	0.96
40	3.583E-10	3.577E-10	3.589E-10	3.590E-10	3.589E-10	3.589E-10	3.568E-10	3.568E-10	3.567E-10	3.587E-10	3.653E-10	3.588E-10	3.589E-10	3.558E-10	3.568E-10	3.584E-10	0.61
60	5.051E-10	5.043E-10	5.057E-10	5.058E-10	5.057E-10	5.057E-10	5.035E-10	5.035E-10	5.033E-10	5.054E-10	5.120E-10	5.056E-10	5.037E-10	5.016E-10	5.035E-10	5.050E-10	0.46
80	6.610E-10	6.599E-10	6.616E-10	6.617E-10	6.616E-10	6.616E-10	6.593E-10	6.593E-10	6.592E-10	6.612E-10	6.680E-10	6.615E-10	6.596E-10	6.564E-10	6.594E-10	6.608E-10	0.37
100	8.262E-10	8.248E-10	8.268E-10	8.269E-10	8.268E-10	8.268E-10	8.244E-10	8.244E-10	8.242E-10	8.262E-10	8.331E-10	8.267E-10	8.248E-10	8.204E-10	8.245E-10	8.258E-10	0.32
120	1.001E-09	9.988E-10	1.001E-09	1.001E-09	1.001E-09	1.001E-09	9.986E-10	9.986E-10	9.983E-10	1.000E-09	1.007E-09	1.001E-09	9.991E-10	9.935E-10	9.987E-10	9.999E-10	0.28
150	1.278E-09	1.276E-09	1.279E-09	1.279E-09	1.279E-09	1.279E-09	1.276E-09	1.276E-09	1.276E-09	1.344E-09	1.285E-09	1.279E-09	1.277E-09	1.273E-09	1.276E-09	1.282E-09	1.36
200	1.783E-09	1.780E-09	1.784E-09	1.784E-09	1.784E-09	1.784E-09	1.781E-09	1.781E-09	1.781E-09	1.875E-09	1.790E-09	1.783E-09	1.782E-09	1.778E-09	1.781E-09	1.789E-09	1.35
300	2.936E-09	2.930E-09	2.936E-09	2.936E-09	2.936E-09	2.936E-09	2.933E-09	2.933E-09	2.932E-09	3.079E-09	2.943E-09	2.935E-09	2.997E-09	2.930E-09	2.933E-09	2.948E-09	1.35
500	5.714E-09	5.704E-09	5.716E-09	5.715E-09	5.715E-09	5.713E-09	5.710E-09	5.710E-09	5.709E-09	5.961E-09	5.721E-09	5.714E-09	5.775E-09	5.709E-09	5.711E-09	5.733E-09	1.14
1 000	1.450E-08	1.447E-08	1.450E-08	1.450E-08	1.450E-08	1.450E-08	1.449E-08	1.449E-08	1.449E-08	1.500E-08	1.451E-08	1.450E-08	1.456E-08	1.448E-08	1.449E-08	1.453E-08	0.90
2 000	3.550E-08	3.544E-08	3.551E-08	3.551E-08	3.550E-08	3.550E-08	3.549E-08	3.549E-08	3.549E-08	3.651E-08	3.551E-08	3.550E-08	3.556E-08	3.544E-08	3.549E-08	3.556E-08	0.74
5 000	1.025E-07	1.024E-07	1.026E-07	1.026E-07	1.025E-07	1.025E-07	1.025E-07	1.025E-07	1.025E-07	1.051E-07	1.026E-07	1.025E-07	1.026E-07	1.024E-07	1.025E-07	1.027E-07	0.64
8 000	1.691E-07	1.688E-07	1.691E-07	1.691E-07	1.691E-07	1.691E-07	1.691E-07	1.691E-07	1.691E-07	1.731E-07	1.691E-07	1.691E-07	1.692E-07	1.689E-07	1.691E-07	1.693E-07	0.62
10 000	2.129E-07	2.126E-07	2.130E-07	2.130E-07	2.130E-07	2.129E-07	2.129E-07	2.129E-07	2.129E-07	2.180E-07	2.130E-07	2.129E-07	2.128E-07	2.127E-07	2.129E-07	2.132E-07	0.62
15 000	3.208E-07	3.203E-07	3.208E-07	3.209E-07	3.208E-07	3.208E-07	3.208E-07	3.208E-07	3.208E-07	3.283E-07	3.209E-07	3.208E-07	3.207E-07	3.205E-07	3.208E-07	3.213E-07	0.61
20 000	4.262E-07	4.255E-07	4.263E-07	4.263E-07	4.263E-07	4.263E-07	4.262E-07	4.262E-07	4.261E-07	4.356E-07	4.263E-07	4.262E-07	4.261E-07	4.259E-07	4.262E-07	4.268E-07	0.57
25 000	5.292E-07	5.283E-07	5.292E-07	5.293E-07	5.292E-07	5.292E-07	5.292E-07	5.292E-07	5.291E-07	5.383E-07	5.293E-07	5.291E-07	5.291E-07	5.288E-07	5.291E-07	5.297E-07	0.45
30 000	6.298E-07	6.287E-07	6.298E-07	6.299E-07	6.298E-07	6.298E-07	6.298E-07	6.298E-07	6.296E-07	6.386E-07	6.299E-07	6.297E-07	6.297E-07	6.293E-07	6.297E-07	6.303E-07	0.37
40 000	8.240E-07	8.225E-07	8.240E-07	8.242E-07	8.241E-07	8.241E-07	8.240E-07	8.240E-07	8.237E-07	8.323E-07	8.241E-07	8.239E-07	8.239E-07	8.234E-07	8.239E-07	8.244E-07	0.27
45 000	9.178E-07	9.161E-07	9.178E-07	9.179E-07	9.178E-07	9.178E-07	9.177E-07	9.177E-07	9.173E-07	9.258E-07	9.178E-07	9.176E-07	9.170E-07	9.171E-07	9.176E-07	9.181E-07	0.24
50 000	1.009E-06	1.007E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	1.017E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	1.009E-06	0.22
100 000	1.814E-06	1.810E-06	1.814E-06	1.814E-06	1.814E-06	1.814E-06	1.814E-06	1.814E-06	1.812E-06	1.819E-06	1.814E-06	1.813E-06	1.813E-06	1.813E-06	1.813E-06	1.814E-06	0.11
500 000	4.178E-06	4.171E-06	4.178E-06	4.178E-06	4.178E-06	4.179E-06	4.179E-06	4.179E-06	4.164E-06	4.179E-06	4.178E-06	4.177E-06	4.178E-06	4.183E-06	4.178E-06	4.177E-06	0.10
1 000 000	4.028E-06	4.022E-06	4.028E-06	4.028E-06	4.028E-06	4.030E-06	4.029E-06	4.029E-06	4.011E-06	4.029E-06	4.028E-06	4.027E-06	4.028E-06	4.037E-06	4.028E-06	4.027E-06	0.14

[a] ENDF/B-VI decay data.
[b] JEFF-3.1 decay data.

Figure 44. Relative difference from sample mean as a function of decay time for ^{233}U atom density



1. Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.
2. Small deviations might occur in the ORIGEN-X-2008 calculated concentrations for times beyond 150 years due to a splitting of the calculation and due to the choice of large time steps.

Table 65. ^{233}U half-life and associated uncertainty values

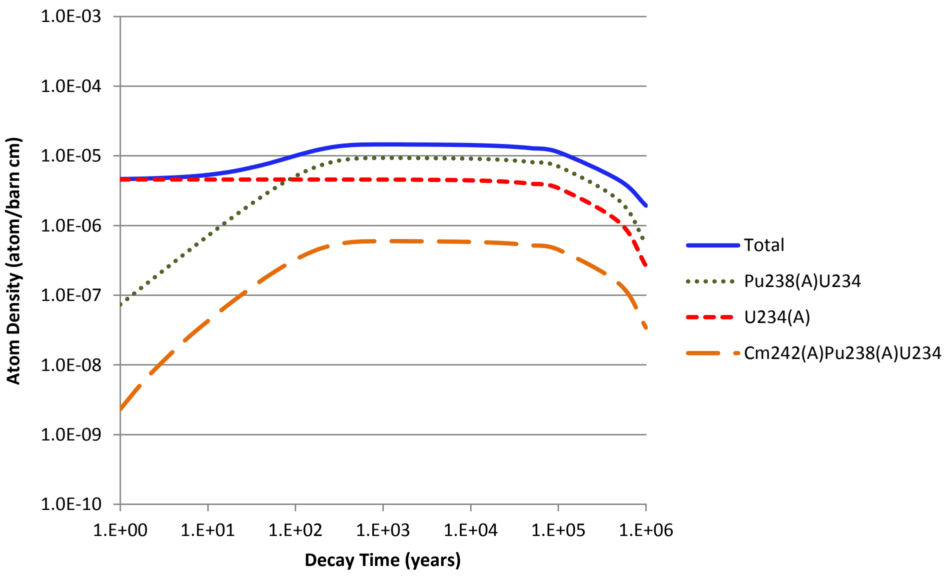
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	5.02396E+12	5.02386E+12	5.02555E+12	5.01755E+12	5.02396E+12	5.00200E+ 12
Uncertainty (s)	6.31152E+09	6.311385E+09	6.31152E+09	-	6.31151E+09	-

Sources: References 12–14, 20 and 21.

3.33. Time-dependent ^{234}U atom densities

^{234}U is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of 2.455×10^{5} ± 600 years and decays by alpha-particle emission and spontaneous fission [20]. ^{234}U concentrations increase with the decay time primarily as a result of ^{238}Pu ($T_{1/2}$ = 87.7 ± 0.1 years) alpha decay. The cumulative ^{234}U atom density and individual contributions from decay chains forming ^{234}U are shown as a function of decay time in Figure 45.

Figure 45. ^{234}U atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 66. In the table, the calculated ^{234}U atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{234}U using the evaluated decay codes/data libraries is illustrated in Figure 46. As seen in the figure, ^{234}U atom densities calculated using TIBSO significantly differ from the other calculated ^{234}U atom densities at long decay times (e.g. by approximately 60% at 10^{6} years). The ^{234}U half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 67.

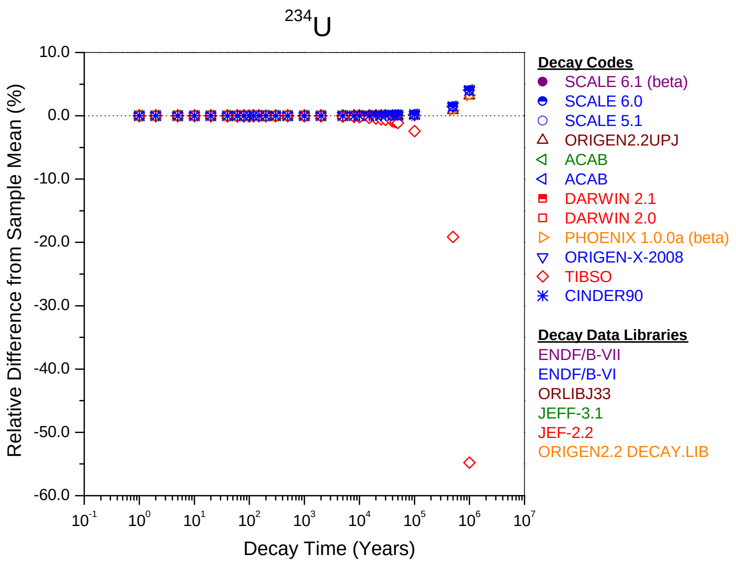
Table 66. Decay calculation results for ^{234}U (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	4.573E-06	0.00
1	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	4.648E-06	4.649E-06	4.649E-06	4.649E-06	4.649E-06	0.01
2	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	4.726E-06	4.727E-06	4.727E-06	4.727E-06	4.727E-06	0.01
5	4.958E-06	4.957E-06	4.957E-06	4.958E-06	4.957E-06	4.957E-06	4.957E-06	4.957E-06	4.957E-06	4.957E-06	4.957E-06	4.956E-06	4.957E-06	4.957E-06	4.957E-06	4.957E-06	0.01
10	5.330E-06	5.330E-06	5.330E-06	5.330E-06	5.330E-06	5.330E-06	5.330E-06	5.330E-06	5.329E-06	5.329E-06	5.330E-06	5.329E-06	5.330E-06	5.329E-06	5.330E-06	5.330E-06	0.01
20	6.033E-06	6.033E-06	6.033E-06	6.033E-06	6.032E-06	6.032E-06	6.033E-06	6.033E-06	6.031E-06	6.032E-06	6.032E-06	6.031E-06	6.032E-06	6.031E-06	6.033E-06	6.032E-06	0.01
40	7.282E-06	7.282E-06	7.282E-06	7.282E-06	7.282E-06	7.282E-06	7.282E-06	7.282E-06	7.280E-06	7.280E-06	7.282E-06	7.280E-06	7.282E-06	7.280E-06	7.282E-06	7.281E-06	0.01
60	8.350E-06	8.349E-06	8.349E-06	8.349E-06	8.348E-06	8.348E-06	8.349E-06	8.349E-06	8.346E-06	8.347E-06	8.349E-06	8.346E-06	8.349E-06	8.347E-06	8.349E-06	8.348E-06	0.02
80	9.261E-06	9.260E-06	9.260E-06	9.261E-06	9.260E-06	9.260E-06	9.260E-06	9.260E-06	9.257E-06	9.258E-06	9.260E-06	9.258E-06	9.260E-06	9.258E-06	9.260E-06	9.259E-06	0.01
100	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	1.004E-05	0.02
120	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	1.070E-05	0.02
150	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	1.152E-05	0.02
200	1.253E-05	1.252E-05	1.252E-05	1.253E-05	1.252E-05	1.252E-05	1.253E-05	1.253E-05	1.252E-05	1.253E-05	1.252E-05	1.252E-05	1.252E-05	1.252E-05	1.252E-05	1.252E-05	0.03
300	1.366E-05	1.366E-05	1.365E-05	1.366E-05	1.366E-05	1.366E-05	1.366E-05	1.366E-05	1.365E-05	1.366E-05	1.365E-05	1.365E-05	1.365E-05	1.365E-05	1.365E-05	1.365E-05	0.02
500	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	1.440E-05	0.01
1 000	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.458E-05	1.457E-05	1.458E-05	1.457E-05	1.458E-05	1.458E-05	0.02
2 000	1.455E-05	1.454E-05	1.454E-05	1.455E-05	1.455E-05	1.455E-05	1.455E-05	1.455E-05	1.455E-05	1.455E-05	1.454E-05	1.454E-05	1.454E-05	1.454E-05	1.454E-05	1.454E-05	0.02
5 000	1.443E-05	1.443E-05	1.443E-05	1.443E-05	1.443E-05	1.443E-05	1.443E-05	1.443E-05	1.443E-05	1.444E-05	1.443E-05	1.443E-05	1.443E-05	1.442E-05	1.443E-05	1.443E-05	0.03
8 000	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.432E-05	1.429E-05	1.432E-05	1.432E-05	0.05
10 000	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.425E-05	1.424E-05	1.425E-05	1.421E-05	1.425E-05	1.425E-05	0.06
15 000	1.407E-05	1.406E-05	1.406E-05	1.407E-05	1.407E-05	1.407E-05	1.407E-05	1.407E-05	1.406E-05	1.407E-05	1.406E-05	1.406E-05	1.406E-05	1.402E-05	1.406E-05	1.406E-05	0.09
20 000	1.389E-05	1.388E-05	1.388E-05	1.389E-05	1.389E-05	1.389E-05	1.388E-05	1.388E-05	1.388E-05	1.389E-05	1.388E-05	1.388E-05	1.388E-05	1.382E-05	1.388E-05	1.388E-05	0.12
25 000	1.371E-05	1.371E-05	1.371E-05	1.371E-05	1.371E-05	1.371E-05	1.371E-05	1.371E-05	1.370E-05	1.371E-05	1.371E-05	1.370E-05	1.371E-05	1.363E-05	1.371E-05	1.370E-05	0.15
30 000	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.353E-05	1.343E-05	1.353E-05	1.352E-05	0.18
40 000	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.318E-05	1.319E-05	1.319E-05	1.319E-05	1.319E-05	1.306E-05	1.319E-05	1.318E-05	0.25
45 000	1.302E-05	1.302E-05	1.302E-05	1.302E-05	1.302E-05	1.302E-05	1.302E-05	1.302E-05	1.301E-05	1.302E-05	1.302E-05	1.302E-05	1.302E-05	1.288E-05	1.302E-05	1.301E-05	0.28
50 000	1.286E-05	1.285E-05	1.285E-05	1.286E-05	1.286E-05	1.286E-05	1.286E-05	1.286E-05	1.285E-05	1.286E-05	1.286E-05	1.285E-05	1.286E-05	1.270E-05	1.286E-05	1.284E-05	0.32
100 000	1.132E-05	1.132E-05	1.132E-05	1.132E-05	1.132E-05	1.132E-05	1.132E-05	1.132E-05	1.131E-05	1.133E-05	1.132E-05	1.132E-05	1.132E-05	1.103E-05	1.132E-05	1.130E-05	0.67
500 000	4.481E-06	4.475E-06	4.476E-06	4.480E-06	4.480E-06	4.480E-06	4.480E-06	4.480E-06	4.453E-06	4.483E-06	4.480E-06	4.479E-06	4.480E-06	3.571E-06	4.480E-06	4.417E-06	5.30
1 000 000	2.006E-06	2.003E-06	2.003E-06	2.006E-06	2.006E-06	2.006E-06	2.006E-06	2.006E-06	1.990E-06	2.008E-06	2.006E-06	2.005E-06	2.006E-06	8.722E-07	2.006E-06	1.929E-06	15.16

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 46. Relative difference from sample mean as a function of decay time for ^{234}U atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 67. ^{234}U half-life and associated uncertainty value

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	7.74739E+12	7.75354E+12	7.75370E+12	7.76300E+12	7.74738E+12	7.71600E+12
Uncertainty (s)	1.89345E+10	9.46708E+09	9.46728E+09	-	1.89345E+10	-

Sources: References 12–14, 20 and 21.

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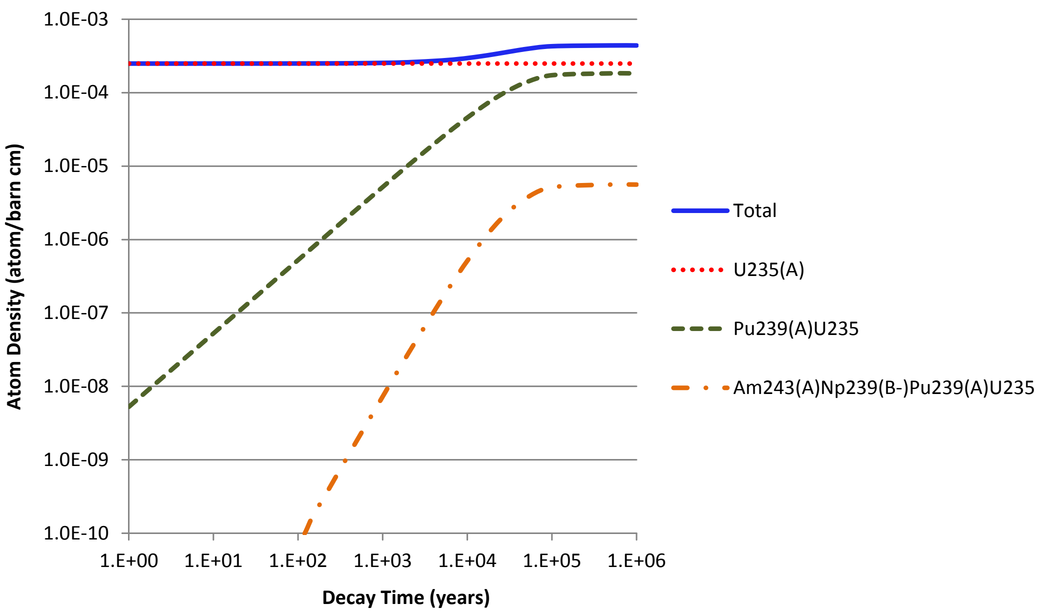
3.34. Time-dependent ^{235}U atom densities

^{235}U is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $7.04{\times}10^8 \pm 10^6$ years and decays by alpha-particle emission and spontaneous fission [20]. ^{235}U concentrations increase after fuel discharge primarily as a result of ^{239}Pu ($T_{1/2} = 2.411{\times}10^4 \pm 30$ years) alpha decay. The cumulative ^{235}U atom density and individual contributions from decay chains forming ^{235}U are shown as a function of decay time in Figure 47.

Figure 47. ^{235}U atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 68. In the table, the calculated ^{235}U atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{235}U using the evaluated decay codes/data libraries is illustrated in Figure 48. All ^{235}U atom density results at any given decay time are practically identical. The ^{235}U half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 69; ^{239}Pu half-life values are presented in Table 78.

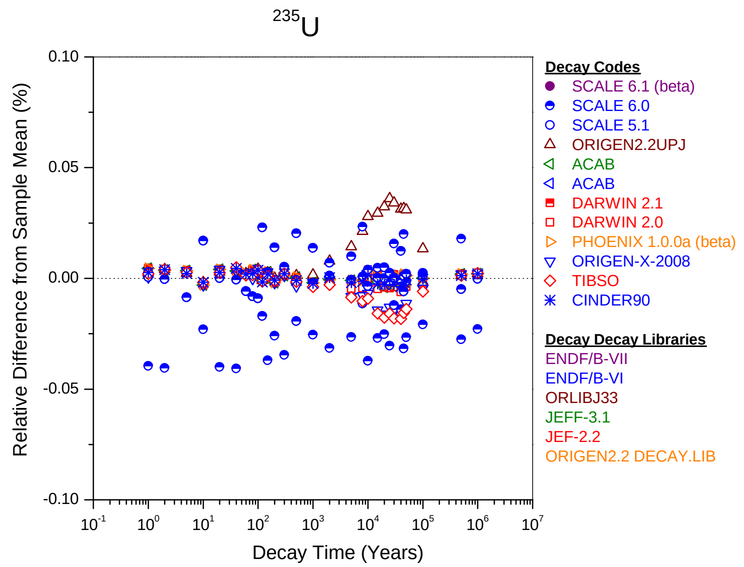
Table 68. Decay calculation results for ^{235}U (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	0.00
1	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.494E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	0.01
2	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.494E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	0.01
5	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	2.495E-04	0.01
10	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.495E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	0.01
20	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	2.495E-04	2.496E-04	2.496E-04	2.496E-04	2.496E-04	0.01
40	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	2.496E-04	2.497E-04	2.497E-04	2.497E-04	2.497E-04	0.01
60	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	2.498E-04	0.00
80	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	2.499E-04	0.01
100	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	2.500E-04	0.01
120	2.502E-04	2.501E-04	2.501E-04	2.502E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	2.501E-04	0.01
150	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	2.502E-04	2.503E-04	2.503E-04	2.503E-04	2.503E-04	0.01
200	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	2.505E-04	2.506E-04	2.506E-04	2.506E-04	2.506E-04	0.01
300	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	2.510E-04	2.511E-04	2.511E-04	2.511E-04	2.511E-04	0.01
500	2.522E-04	2.522E-04	2.522E-04	2.522E-04	2.522E-04	2.522E-04	2.522E-04	2.522E-04	2.522E-04	2.521E-04	2.521E-04	2.521E-04	2.521E-04	2.521E-04	2.521E-04	2.521E-04	0.01
1 000	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	2.547E-04	2.548E-04	2.548E-04	2.548E-04	2.548E-04	0.01
2 000	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	2.598E-04	2.599E-04	2.599E-04	2.599E-04	2.599E-04	0.01
5 000	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.745E-04	2.744E-04	2.745E-04	2.744E-04	2.745E-04	2.745E-04	0.01
8 000	2.879E-04	2.879E-04	2.880E-04	2.880E-04	2.879E-04	2.879E-04	2.879E-04	2.879E-04	2.880E-04	2.879E-04	2.879E-04	2.879E-04	2.879E-04	2.879E-04	2.879E-04	2.879E-04	0.01
10 000	2.963E-04	2.963E-04	2.964E-04	2.963E-04	2.963E-04	2.963E-04	2.963E-04	2.963E-04	2.964E-04	2.963E-04	2.963E-04	2.962E-04	2.963E-04	2.963E-04	2.963E-04	2.963E-04	0.01
15 000	3.154E-04	3.154E-04	3.155E-04	3.154E-04	3.154E-04	3.154E-04	3.154E-04	3.154E-04	3.155E-04	3.153E-04	3.154E-04	3.153E-04	3.154E-04	3.153E-04	3.154E-04	3.154E-04	0.01
20 000	3.320E-04	3.320E-04	3.321E-04	3.320E-04	3.320E-04	3.320E-04	3.320E-04	3.320E-04	3.321E-04	3.319E-04	3.320E-04	3.319E-04	3.320E-04	3.319E-04	3.320E-04	3.320E-04	0.02
25 000	3.464E-04	3.464E-04	3.465E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04	3.465E-04	3.464E-04	3.464E-04	3.463E-04	3.464E-04	3.464E-04	3.464E-04	3.464E-04	0.02
30 000	3.589E-04	3.590E-04	3.591E-04	3.590E-04	3.589E-04	3.589E-04	3.589E-04	3.589E-04	3.591E-04	3.589E-04	3.589E-04	3.589E-04	3.589E-04	3.589E-04	3.589E-04	3.589E-04	0.02
40 000	3.792E-04	3.793E-04	3.794E-04	3.793E-04	3.792E-04	3.792E-04	3.792E-04	3.792E-04	3.794E-04	3.792E-04	3.793E-04	3.792E-04	3.793E-04	3.792E-04	3.792E-04	3.793E-04	0.02
45 000	3.874E-04	3.874E-04	3.875E-04	3.875E-04	3.874E-04	3.874E-04	3.874E-04	3.874E-04	3.875E-04	3.874E-04	3.874E-04	3.873E-04	3.874E-04	3.874E-04	3.874E-04	3.874E-04	0.02
50 000	3.945E-04	3.945E-04	3.946E-04	3.945E-04	3.945E-04	3.945E-04	3.945E-04	3.945E-04	3.946E-04	3.945E-04	3.945E-04	3.944E-04	3.945E-04	3.945E-04	3.945E-04	3.945E-04	0.01
100 000	4.295E-04	4.295E-04	4.295E-04	4.295E-04	4.295E-04	4.295E-04	4.295E-04	4.295E-04	4.296E-04	4.295E-04	4.295E-04	4.294E-04	4.295E-04	4.295E-04	4.295E-04	4.295E-04	0.01
500 000	4.402E-04	4.402E-04	4.402E-04	4.403E-04	4.402E-04	4.402E-04	4.402E-04	4.402E-04	4.402E-04	4.402E-04	4.402E-04	4.401E-04	4.402E-04	4.402E-04	4.402E-04	4.402E-04	0.01
1 000 000	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	4.399E-04	4.400E-04	4.400E-04	4.400E-04	4.400E-04	0.01

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 48. Relative difference from sample mean as a function of decay time for ^{235}U atom density



Note: For a decay code using multiple sources of decay data, only the primary decay data source is indicated in the figure.

Table 69. ^{235}U half-life and associated uncertainty value

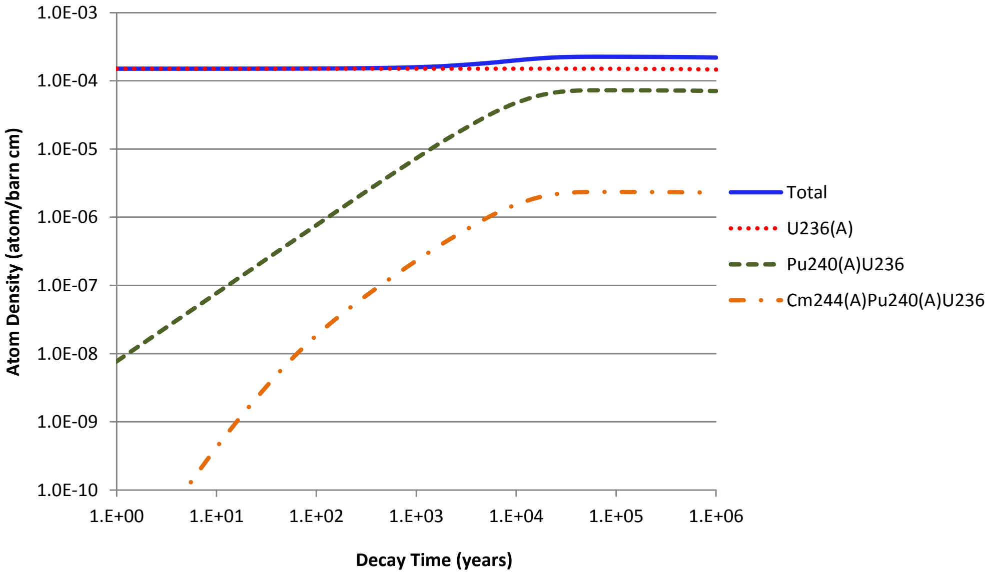
Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.22165E+16	2.22066E+16	2.22102E+16	2.22165E+16	2.22100E+16
Uncertainty (s)	3.15576E+13	2.20899E+13	1.57788E+13	-	-

Sources: References 12, 13, 20 and 21.

3.35. Time-dependent ^{236}U atom densities

^{236}U is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $2.342\times10^7 \pm 3\times10^4$ years and decays by alpha-particle emission and spontaneous fission [20]. The ^{236}U atom density increases after approximately 10^3 years from fuel discharge primarily as a result of ^{240}Pu ($T_{1/2} = 6.561\times10^3 \pm 7$ years) alpha decay. The cumulative ^{236}U atom density and individual contributions from decay chains forming ^{236}U are shown as a function of decay time in Figure 49.

Figure 49. ^{236}U atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 70. In the table, the calculated ^{236}U atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{236}U using the evaluated decay codes/data libraries is illustrated in Figure 50. All ^{236}U atom density results at any given decay time are practically identical. The ^{236}U half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 71; ^{240}Pu half-life values are presented in Table 80.

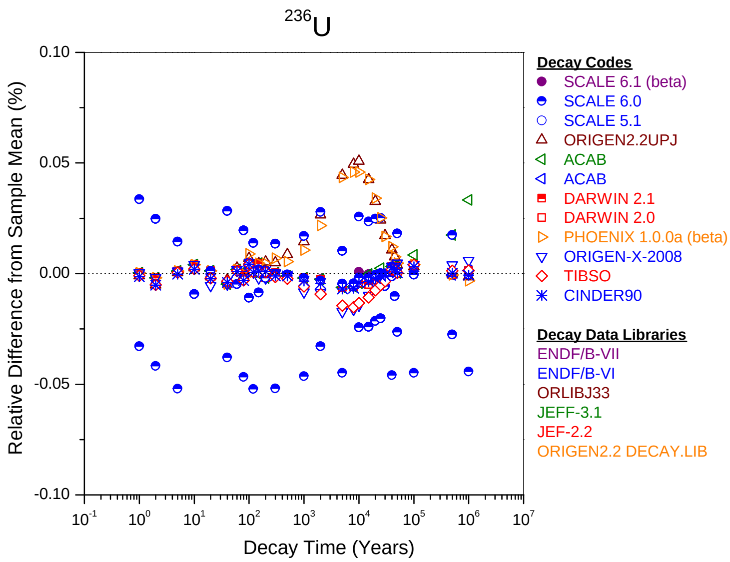
Table 70. Decay calculation results for ^{236}U (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	0.00
1	1.505E-04	1.505E-04	1.504E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	1.504E-04	0.02
2	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.504E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	0.02
5	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.504E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	0.02
10	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	1.505E-04	0.01
20	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	1.506E-04	0.00
40	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	1.507E-04	1.508E-04	1.508E-04	1.508E-04	1.508E-04	0.02
60	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	1.509E-04	0.00
80	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	1.510E-04	1.511E-04	1.511E-04	1.511E-04	1.511E-04	0.02
100	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	1.512E-04	0.01
120	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	1.513E-04	1.514E-04	1.514E-04	1.514E-04	1.514E-04	0.02
150	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	1.516E-04	0.01
200	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	1.520E-04	0.00
300	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	1.527E-04	1.528E-04	1.528E-04	1.528E-04	1.528E-04	0.02
500	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	1.543E-04	0.00
1 000	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	1.579E-04	1.580E-04	1.580E-04	1.580E-04	1.580E-04	0.02
2 000	1.648E-04	1.648E-04	1.648E-04	1.648E-04	1.648E-04	1.648E-04	1.648E-04	1.648E-04	1.648E-04	1.647E-04	1.647E-04	1.647E-04	1.647E-04	1.647E-04	1.647E-04	1.648E-04	0.02
5 000	1.813E-04	1.813E-04	1.814E-04	1.813E-04	1.813E-04	1.813E-04	1.813E-04	1.813E-04	1.814E-04	1.813E-04	1.813E-04	1.812E-04	1.813E-04	1.813E-04	1.813E-04	1.813E-04	0.02
8 000	1.933E-04	1.933E-04	1.934E-04	1.933E-04	1.933E-04	1.933E-04	1.933E-04	1.933E-04	1.934E-04	1.933E-04	1.933E-04	1.933E-04	1.933E-04	1.933E-04	1.933E-04	1.933E-04	0.02
10 000	1.994E-04	1.995E-04	1.996E-04	1.995E-04	1.994E-04	1.994E-04	1.994E-04	1.994E-04	1.995E-04	1.994E-04	1.994E-04	1.994E-04	1.994E-04	1.994E-04	1.994E-04	1.994E-04	0.02
15 000	2.101E-04	2.102E-04	2.102E-04	2.102E-04	2.102E-04	2.102E-04	2.101E-04	2.101E-04	2.102E-04	2.101E-04	2.101E-04	2.101E-04	2.101E-04	2.101E-04	2.101E-04	2.102E-04	0.02
20 000	2.164E-04	2.164E-04	2.165E-04	2.165E-04	2.164E-04	2.164E-04	2.164E-04	2.164E-04	2.165E-04	2.164E-04	2.164E-04	2.164E-04	2.164E-04	2.164E-04	2.164E-04	2.164E-04	0.02
25 000	2.201E-04	2.201E-04	2.202E-04	2.202E-04	2.201E-04	2.202E-04	2.201E-04	2.201E-04	2.202E-04	2.201E-04	2.201E-04	2.201E-04	2.201E-04	2.201E-04	2.201E-04	2.201E-04	0.01
30 000	2.223E-04	2.223E-04	2.224E-04	2.223E-04	2.223E-04	2.223E-04	2.223E-04	2.223E-04	2.224E-04	2.223E-04	2.223E-04	2.223E-04	2.223E-04	2.223E-04	2.223E-04	2.223E-04	0.01
40 000	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	2.242E-04	2.243E-04	2.243E-04	2.243E-04	2.243E-04	0.01
45 000	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	2.247E-04	0.01
50 000	2.249E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.249E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	0.01
100 000	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	2.249E-04	2.250E-04	2.250E-04	2.250E-04	2.250E-04	0.01
500 000	2.223E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	2.223E-04	2.224E-04	2.224E-04	2.224E-04	2.224E-04	0.01
1 000 000	2.191E-04	2.191E-04	2.191E-04	2.191E-04	2.191E-04	2.192E-04	2.191E-04	2.191E-04	2.191E-04	2.191E-04	2.191E-04	2.190E-04	2.191E-04	2.191E-04	2.191E-04	2.191E-04	0.01

[a] SCALE 6.0/ORIGEN data libraries.

[b] JEFF-3.1 decay data.

Figure 50. Relative difference from sample mean as a function of decay time for ^{236}U atom density



Note: For a decay code using multiple sources of decay data, only the primary decay data source is indicated in the figure.

Table 71. ^{236}U half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN 2.2 DECAY.LIB
Half-life (s)	7.39078E+14	7.39063E+14	7.47915E+14	7.38447E+14	7.39078E+14	7.38900E+14
Uncertainty (s)	9.46728E+11	9.46708E+11	6.31152E+12	-	9.46726E+11	-

Sources: References 12–14, 20 and 21.

3.36. Time-dependent ^{238}U atom densities

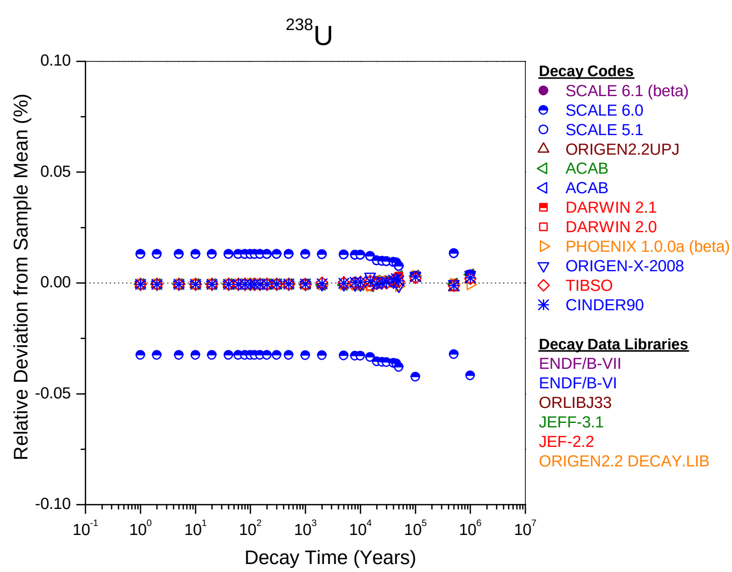
^{238}U is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $4.468\times10^9 \pm 3\times10^6$ years and decays by alpha-particle emission and spontaneous fission [20]. No significant contribution from parent nuclides occurs over the one-million time period. The ^{238}U half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 72. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 73. In the table, the calculated ^{238}U atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{238}U using the evaluated decay codes/data libraries is illustrated in Figure 51. All ^{238}U atom density results at any given decay time are practically identical.

Table 72. ^{238}U half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.40999E+17	1.40996E+17	1.40996E+17	1.41059E+17	1.41000E+17
Uncertainty (s)	9.46728E+13	1.57785E+14	9.46708E+13	-	-

Sources: References 12–13, 20 and 21.

Figure 51. Relative difference from sample mean as a function of decay time for ^{238}U atom density



Note: For a decay code using multiple sources of decay data, only the primary decay data source is indicated in the figure.

Table 73. Decay calculation results for ^{238}U (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United SCALE 6.1	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	USA CINDER90	Sample mean	RSD (%)
0	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.00
1	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
2	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
5	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
10	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
20	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
40	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
60	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
80	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
100	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
120	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
150	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
200	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
300	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
500	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
1 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
2 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
5 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
8 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
10 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
15 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
20 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
25 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
30 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
40 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
45 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
50 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
100 000	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	2.194E-02	2.195E-02	2.195E-02	2.195E-02	2.195E-02	0.01
500 000	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.195E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	0.01
1 000 000	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	2.195E-02	2.196E-02	2.196E-02	2.196E-02	2.196E-02	0.01

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

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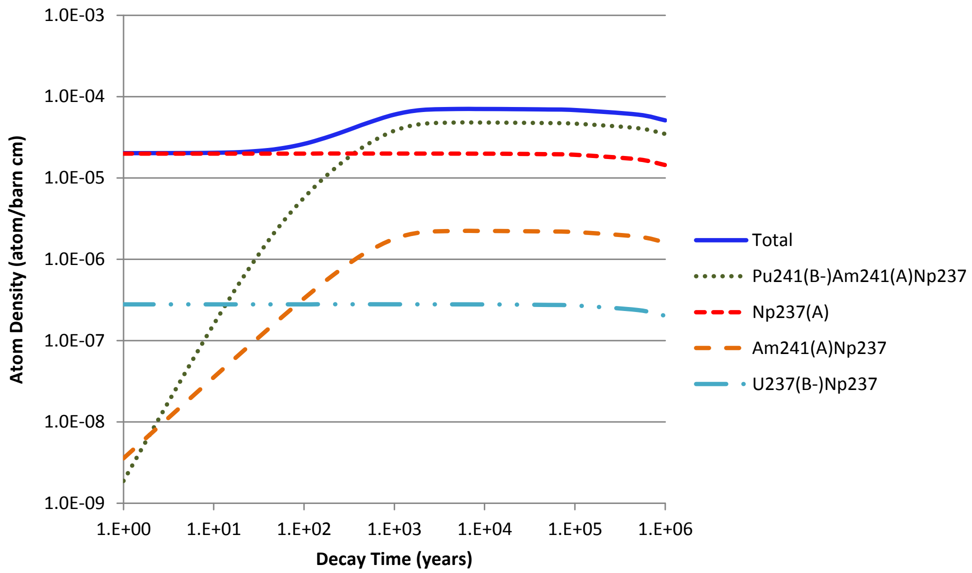
3.37. Time-dependent ^{237}Np atom densities

^{237}Np is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $2.144 \times 10^6 \pm 7 \times 10^3$ years and decays by alpha-particle emission [20]. ^{237}Np concentrations increase with decay time primarily as a result of ^{241}Pu and ^{241}Am decay. The cumulative ^{237}Np atom density and individual contributions from decay chains forming ^{237}Np are shown as a function of decay time in Figure 52.

Figure 52. ^{237}Np atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up;
A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 74. In the table, the calculated ^{237}Np atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{237}Np using the evaluated decay codes/data libraries is illustrated in Figure 53. The dispersion of the decay calculation results is insignificant at long decay times, which is an indication of similar decay data used in the calculations. Small deviations occurred in the ^{237}Np atom densities for decay times greater than 150 years calculated with ORIGEN-X-2008 due to a splitting of the calculation and due to the choice of large time steps, which affected ^{237}Np contributions from ^{241}Pu decay (see Appendix B). The half-life values for ^{237}Np and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 75; decay data for ^{241}Pu and ^{241}Am are presented in Table 82 and Table 87, respectively.

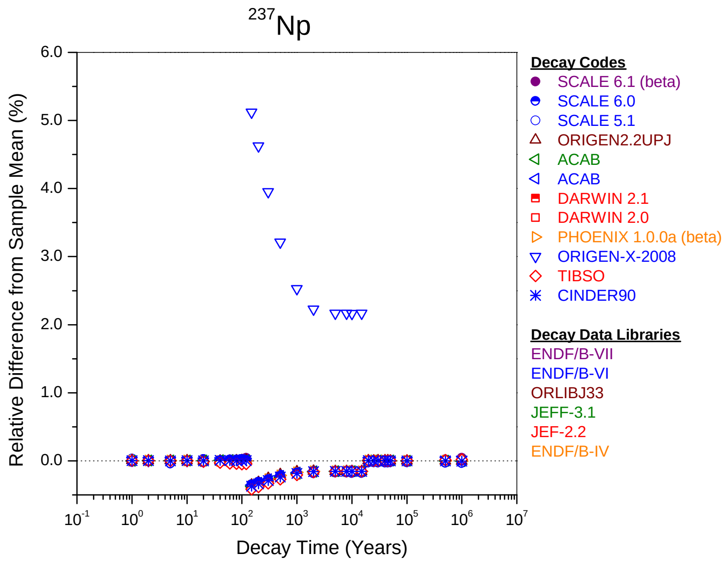
Table 74. Decay calculation results for ^{237}Np (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	1.989E-05	0.00
1	2.018E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	2.017E-05	0.01
2	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	2.018E-05	0.00
5	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	2.022E-05	2.023E-05	2.023E-05	2.023E-05	2.023E-05	0.01
10	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	2.036E-05	0.00
20	2.079E-05	2.079E-05	2.078E-05	2.079E-05	2.079E-05	2.079E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	2.078E-05	0.01
40	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.198E-05	2.197E-05	2.198E-05	2.198E-05	0.01
60	2.337E-05	2.337E-05	2.337E-05	2.337E-05	2.337E-05	2.337E-05	2.336E-05	2.336E-05	2.336E-05	2.337E-05	2.337E-05	2.336E-05	2.337E-05	2.336E-05	2.337E-05	2.337E-05	0.02
80	2.480E-05	2.480E-05	2.480E-05	2.480E-05	2.480E-05	2.480E-05	2.479E-05	2.479E-05	2.479E-05	2.479E-05	2.480E-05	2.479E-05	2.480E-05	2.478E-05	2.480E-05	2.480E-05	0.02
100	2.622E-05	2.622E-05	2.621E-05	2.622E-05	2.622E-05	2.621E-05	2.621E-05	2.621E-05	2.621E-05	2.621E-05	2.622E-05	2.621E-05	2.622E-05	2.620E-05	2.621E-05	2.621E-05	0.02
120	2.760E-05	2.760E-05	2.760E-05	2.760E-05	2.760E-05	2.760E-05	2.759E-05	2.759E-05	2.760E-05	2.760E-05	2.760E-05	2.759E-05	2.760E-05	2.759E-05	2.760E-05	2.760E-05	0.02
150	2.961E-05	2.961E-05	2.961E-05	2.961E-05	2.961E-05	2.960E-05	2.960E-05	2.960E-05	2.960E-05	3.123E-05	2.961E-05	2.960E-05	2.961E-05	2.959E-05	2.960E-05	2.971E-05	1.42
200	3.275E-05	3.275E-05	3.275E-05	3.275E-05	3.275E-05	3.274E-05	3.274E-05	3.274E-05	3.274E-05	3.437E-05	3.275E-05	3.274E-05	3.275E-05	3.273E-05	3.274E-05	3.285E-05	1.28
300	3.832E-05	3.832E-05	3.833E-05	3.832E-05	3.832E-05	3.831E-05	3.831E-05	3.831E-05	3.832E-05	3.994E-05	3.832E-05	3.831E-05	3.832E-05	3.830E-05	3.831E-05	3.842E-05	1.09
500	4.711E-05	4.711E-05	4.712E-05	4.712E-05	4.711E-05	4.710E-05	4.710E-05	4.710E-05	4.711E-05	4.873E-05	4.711E-05	4.710E-05	4.711E-05	4.709E-05	4.710E-05	4.722E-05	0.89
1 000	5.994E-05	5.994E-05	5.995E-05	5.994E-05	5.994E-05	5.993E-05	5.993E-05	5.993E-05	5.994E-05	6.156E-05	5.994E-05	5.992E-05	5.994E-05	5.992E-05	5.993E-05	6.004E-05	0.70
2 000	6.826E-05	6.827E-05	6.827E-05	6.827E-05	6.827E-05	6.827E-05	6.827E-05	6.827E-05	6.827E-05	6.990E-05	6.827E-05	6.825E-05	6.827E-05	6.826E-05	6.827E-05	6.838E-05	0.62
5 000	7.031E-05	7.032E-05	7.031E-05	7.032E-05	7.032E-05	7.032E-05	7.031E-05	7.031E-05	7.031E-05	7.195E-05	7.032E-05	7.030E-05	7.032E-05	7.031E-05	7.031E-05	7.042E-05	0.60
8 000	7.028E-05	7.029E-05	7.028E-05	7.029E-05	7.029E-05	7.029E-05	7.028E-05	7.028E-05	7.028E-05	7.192E-05	7.029E-05	7.027E-05	7.029E-05	7.028E-05	7.028E-05	7.039E-05	0.60
10 000	7.025E-05	7.025E-05	7.025E-05	7.026E-05	7.025E-05	7.025E-05	7.025E-05	7.025E-05	7.025E-05	7.188E-05	7.025E-05	7.023E-05	7.025E-05	7.025E-05	7.025E-05	7.036E-05	0.60
15 000	7.015E-05	7.016E-05	7.016E-05	7.016E-05	7.016E-05	7.016E-05	7.016E-05	7.016E-05	7.016E-05	7.179E-05	7.016E-05	7.014E-05	7.016E-05	7.016E-05	7.016E-05	7.027E-05	0.60
20 000	7.005E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	7.004E-05	7.006E-05	7.006E-05	7.006E-05	7.006E-05	0.01
25 000	6.995E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	6.994E-05	6.996E-05	6.996E-05	6.996E-05	6.996E-05	0.01
30 000	6.984E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	6.983E-05	6.985E-05	6.985E-05	6.985E-05	6.985E-05	0.01
40 000	6.962E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	6.961E-05	6.963E-05	6.963E-05	6.963E-05	6.963E-05	0.01
45 000	6.951E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	6.950E-05	6.952E-05	6.952E-05	6.952E-05	6.952E-05	0.01
50 000	6.940E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	6.939E-05	6.941E-05	6.941E-05	6.941E-05	6.941E-05	0.01
100 000	6.829E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.830E-05	6.828E-05	6.830E-05	6.830E-05	6.830E-05	6.829E-05	0.01
500 000	5.999E-05	6.001E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	5.998E-05	6.000E-05	6.000E-05	6.000E-05	6.000E-05	0.01
1 000 000	5.102E-05	5.105E-05	5.103E-05	5.103E-05	5.103E-05	5.103E-05	5.103E-05	5.103E-05	5.103E-05	5.104E-05	5.102E-05	5.101E-05	5.102E-05	5.104E-05	5.103E-05	5.103E-05	0.02

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 53. Relative difference from sample mean as a function of decay time for ^{237}Np atom density



1. Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.
2. Small deviations might occur in the ORIGEN-X-2008 calculated concentrations for times beyond 150 years due to a splitting of the calculation and due to the choice of large time steps.

Table 75. ^{237}Np half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	6.76594E+13	6.75318E+13	6.75318E+13	6.75318E+13	6.75300E+13
Uncertainty (s)	2.20903E+11	3.15569E+11	3.15569E+11	-	-

Sources: References 12, 13, 20 and 21.

3.38. Time-dependent ^{238}Pu atom densities

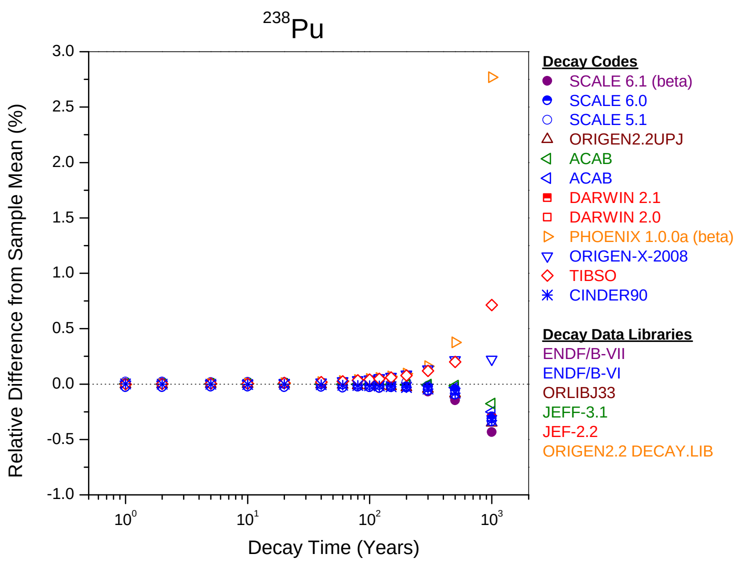
^{238}Pu is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of 87.7 ± 0.1 years and decays by alpha-particle emission [20]. ^{238}Pu fuel concentrations decrease to insignificant levels after approximately 10^3 years from the fuel discharge. ^{242}Cm alpha decay ($T_{1/2}$ = 162.8 ± 0.2 days) contributes up 6% of the ^{238}Pu total atom density; insignificant ^{238}Pu quantities are produced as a result of ^{242m}Am ($T_{1/2}$ = 141 ± 2 years) decay. The ^{238}Pu half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 76. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 77. In the table, the calculated ^{238}Pu atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{238}Pu using the evaluated decay codes/data libraries is illustrated in Figure 54. PHOENIX 1.0.0a (beta) predicts slightly higher ^{238}Pu concentrations at long decay times than the other evaluated decay codes/libraries (e.g. ~3% higher at 10^3 years), as seen in the figure.

Table 76. ^{238}Pu half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.76760E+09	2.76754E+09	2.76754E+09	2.76754E+09	2.76900E+09
Uncertainty (s)	3.15576E+06	9.46708E+06	9.46708E+06	-	-

Sources: References 12, 13, 20 and 21.

Figure 54. Relative difference from sample mean as a function of decay time for ^{238}Pu atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 77. Decay calculation results for ^{238}Pu (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	9.351E-06	0.00
1	9.799E-06	9.797E-06	9.797E-06	9.798E-06	9.797E-06	9.797E-06	9.797E-06	9.797E-06	9.797E-06	9.797E-06	9.797E-06	9.794E-06	9.797E-06	9.797E-06	9.797E-06	9.797E-06	0.01
2	9.822E-06	9.820E-06	9.820E-06	9.821E-06	9.820E-06	9.820E-06	9.820E-06	9.820E-06	9.820E-06	9.820E-06	9.820E-06	9.817E-06	9.820E-06	9.820E-06	9.820E-06	9.820E-06	0.01
5	9.618E-06	9.616E-06	9.616E-06	9.617E-06	9.617E-06	9.617E-06	9.616E-06	9.616E-06	9.617E-06	9.617E-06	9.616E-06	9.614E-06	9.616E-06	9.617E-06	9.616E-06	9.616E-06	0.01
10	9.247E-06	9.245E-06	9.245E-06	9.246E-06	9.245E-06	9.245E-06	9.245E-06	9.245E-06	9.246E-06	9.246E-06	9.245E-06	9.243E-06	9.245E-06	9.246E-06	9.245E-06	9.245E-06	0.01
20	8.546E-06	8.544E-06	8.544E-06	8.545E-06	8.545E-06	8.545E-06	8.544E-06	8.544E-06	8.545E-06	8.546E-06	8.544E-06	8.542E-06	8.545E-06	8.545E-06	8.544E-06	8.545E-06	0.01
40	7.300E-06	7.298E-06	7.299E-06	7.299E-06	7.299E-06	7.299E-06	7.299E-06	7.299E-06	7.300E-06	7.300E-06	7.299E-06	7.297E-06	7.299E-06	7.300E-06	7.298E-06	7.299E-06	0.01
60	6.236E-06	6.234E-06	6.234E-06	6.235E-06	6.235E-06	6.235E-06	6.235E-06	6.235E-06	6.237E-06	6.237E-06	6.235E-06	6.233E-06	6.235E-06	6.237E-06	6.234E-06	6.235E-06	0.02
80	5.327E-06	5.325E-06	5.326E-06	5.326E-06	5.326E-06	5.326E-06	5.326E-06	5.326E-06	5.328E-06	5.328E-06	5.326E-06	5.325E-06	5.326E-06	5.328E-06	5.326E-06	5.326E-06	0.02
100	4.551E-06	4.549E-06	4.550E-06	4.550E-06	4.550E-06	4.550E-06	4.550E-06	4.550E-06	4.552E-06	4.552E-06	4.550E-06	4.549E-06	4.550E-06	4.552E-06	4.550E-06	4.550E-06	0.02
120	3.888E-06	3.886E-06	3.887E-06	3.887E-06	3.887E-06	3.887E-06	3.887E-06	3.887E-06	3.890E-06	3.890E-06	3.887E-06	3.886E-06	3.887E-06	3.889E-06	3.887E-06	3.887E-06	0.03
150	3.070E-06	3.069E-06	3.069E-06	3.070E-06	3.070E-06	3.070E-06	3.069E-06	3.069E-06	3.072E-06	3.072E-06	3.069E-06	3.069E-06	3.069E-06	3.072E-06	3.069E-06	3.070E-06	0.04
200	2.072E-06	2.071E-06	2.071E-06	2.071E-06	2.072E-06	2.072E-06	2.071E-06	2.071E-06	2.074E-06	2.074E-06	2.071E-06	2.071E-06	2.071E-06	2.073E-06	2.071E-06	2.072E-06	0.05
300	9.441E-07	9.436E-07	9.438E-07	9.440E-07	9.441E-07	9.442E-07	9.439E-07	9.439E-07	9.458E-07	9.455E-07	9.440E-07	9.437E-07	9.440E-07	9.454E-07	9.438E-07	9.442E-07	0.07
500	1.971E-07	1.969E-07	1.970E-07	1.971E-07	1.971E-07	1.972E-07	1.971E-07	1.971E-07	1.979E-07	1.976E-07	1.971E-07	1.970E-07	1.971E-07	1.976E-07	1.970E-07	1.972E-07	0.15
1 000	4.197E-09	4.191E-09	4.194E-09	4.197E-09	4.199E-09	4.202E-09	4.196E-09	4.196E-09	4.326E-09	4.219E-09	4.196E-09	4.195E-09	4.196E-09	4.239E-09	4.195E-09	4.209E-09	0.82
2 000	3.007E-12	3.001E-12	5.208E-12	3.007E-12	3.010E-12	3.020E-12	5.219E-12	5.219E-12	7.934E-12	3.034E-12	5.209E-12	3.006E-12	3.007E-12	6.081E-12	5.217E-12	4.279E-12	36.33

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.39. Time-dependent ^{239}Pu atom densities

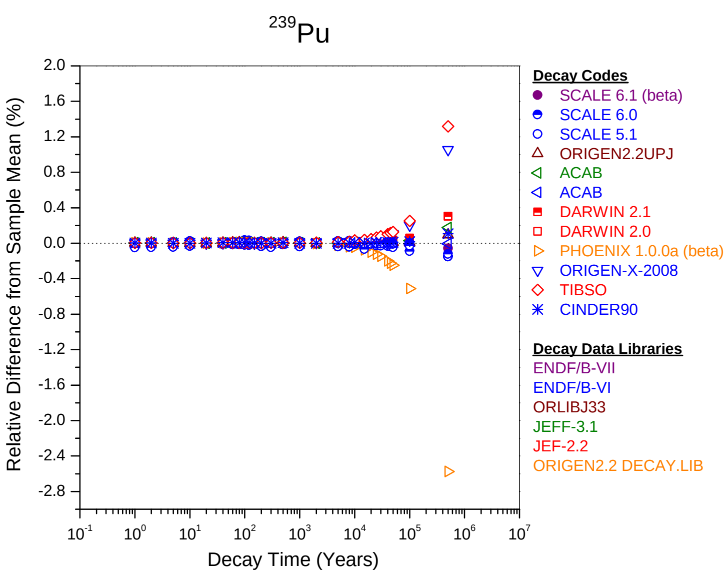
^{239}Pu is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of 2.411×10^4 ± 30 years and decays by alpha-particle emission and spontaneous fission [20]. Approximately 1% of the total ^{239}Pu concentration is produced a short time after fuel discharge as a result of ^{239}Np ($T_{1/2}$ = 2.356 ± 0.003 days) beta decay. ^{243}Am ($T_{1/2}$ = 7.370×10^3 ± 40 years) alpha decay contributes approximately 4% of the total ^{239}Pu atom density at very long decay times. The ^{239}Pu half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 78. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 79. In the table, the calculated ^{239}Pu atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{239}Pu using the evaluated decay codes/data libraries is illustrated in Figure 55. A very small dispersion of the calculated ^{239}Pu atom densities is observed at long decay times (e.g. RSD ≈ 1% at 5×10^5 years), which is may be attributed to the different ^{239}Pu half-life values used.

Table 78. ^{239}Pu half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	7.60853E+11	7.60837E+11	7.60948E+11	7.60522E+11	7.60853E+11	7.59400E+11
Uncertainty (s)	9.46728+E08	9.46708E+08	3.47134E+08	-	9.46728+E08	-

Sources: References 12–14, 20 and 21.

Figure 55. Relative difference from sample mean as a function of decay time for ^{239}Pu atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 79. Decay calculation results for ^{239}Pu (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	1.834E-04	0.00
1	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.852E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	0.01
2	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.852E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	0.01
5	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.852E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	0.01
10	1.852E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	1.852E-04	1.853E-04	1.853E-04	1.853E-04	1.853E-04	0.02
20	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	1.852E-04	0.00
40	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	1.851E-04	0.01
60	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	1.850E-04	0.01
80	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	1.849E-04	0.01
100	1.848E-04	1.848E-04	1.848E-04	1.849E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	0.01
120	1.847E-04	1.848E-04	1.847E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.848E-04	1.847E-04	1.847E-04	1.847E-04	1.847E-04	1.847E-04	1.847E-04	0.01
150	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	1.846E-04	0.00
200	1.843E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	1.843E-04	1.844E-04	1.844E-04	1.844E-04	1.844E-04	0.02
300	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	1.838E-04	1.839E-04	1.839E-04	1.839E-04	1.839E-04	0.01
500	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	1.829E-04	0.01
1 000	1.805E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	1.805E-04	1.806E-04	1.806E-04	1.806E-04	1.806E-04	0.02
2 000	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	1.759E-04	0.00
5 000	1.624E-04	1.625E-04	1.625E-04	1.625E-04	1.625E-04	1.625E-04	1.625E-04	1.625E-04	1.624E-04	1.625E-04	1.625E-04	1.624E-04	1.625E-04	1.625E-04	1.625E-04	1.625E-04	0.02
8 000	1.498E-04	1.499E-04	1.499E-04	1.499E-04	1.499E-04	1.499E-04	1.499E-04	1.499E-04	1.498E-04	1.499E-04	1.499E-04	1.498E-04	1.499E-04	1.499E-04	1.499E-04	1.499E-04	0.02
10 000	1.419E-04	1.419E-04	1.419E-04	1.419E-04	1.419E-04	1.419E-04	1.419E-04	1.419E-04	1.419E-04	1.420E-04	1.419E-04	1.419E-04	1.419E-04	1.420E-04	1.419E-04	1.419E-04	0.02
15 000	1.237E-04	1.237E-04	1.237E-04	1.237E-04	1.237E-04	1.237E-04	1.237E-04	1.237E-04	1.236E-04	1.237E-04	1.237E-04	1.236E-04	1.237E-04	1.237E-04	1.237E-04	1.237E-04	0.03
20 000	1.076E-04	1.076E-04	1.076E-04	1.076E-04	1.076E-04	1.076E-04	1.076E-04	1.076E-04	1.075E-04	1.076E-04	1.076E-04	1.076E-04	1.076E-04	1.077E-04	1.076E-04	1.076E-04	0.03
25 000	9.347E-05	9.348E-05	9.349E-05	9.349E-05	9.349E-05	9.350E-05	9.350E-05	9.350E-05	9.337E-05	9.354E-05	9.348E-05	9.346E-05	9.348E-05	9.355E-05	9.349E-05	9.349E-05	0.04
30 000	8.114E-05	8.115E-05	8.116E-05	8.115E-05	8.116E-05	8.116E-05	8.117E-05	8.117E-05	8.103E-05	8.121E-05	8.115E-05	8.113E-05	8.115E-05	8.122E-05	8.116E-05	8.115E-05	0.05
40 000	6.104E-05	6.104E-05	6.105E-05	6.105E-05	6.105E-05	6.106E-05	6.106E-05	6.106E-05	6.093E-05	6.110E-05	6.104E-05	6.103E-05	6.104E-05	6.111E-05	6.105E-05	6.105E-05	0.07
45 000	5.291E-05	5.291E-05	5.292E-05	5.292E-05	5.292E-05	5.293E-05	5.293E-05	5.293E-05	5.280E-05	5.297E-05	5.291E-05	5.290E-05	5.291E-05	5.298E-05	5.293E-05	5.292E-05	0.08
50 000	4.585E-05	4.586E-05	4.587E-05	4.586E-05	4.586E-05	4.587E-05	4.588E-05	4.588E-05	4.575E-05	4.591E-05	4.586E-05	4.584E-05	4.586E-05	4.592E-05	4.587E-05	4.586E-05	0.09
100 000	1.091E-05	1.091E-05	1.091E-05	1.091E-05	1.091E-05	1.091E-05	1.092E-05	1.092E-05	1.085E-05	1.093E-05	1.091E-05	1.090E-05	1.091E-05	1.094E-05	1.091E-05	1.091E-05	0.17
500 000	1.103E-10	1.104E-10	1.106E-10	1.103E-10	1.105E-10	1.107E-10	1.108E-10	1.108E-10	1.076E-10	1.116E-10	1.103E-10	1.103E-10	1.103E-10	1.119E-10	1.106E-10	1.105E-10	0.84

[a]ENDF/B-VI decay data.

[b]JEFF-3.1 decay data.

3.40. Time-dependent ^{240}Pu atom densities

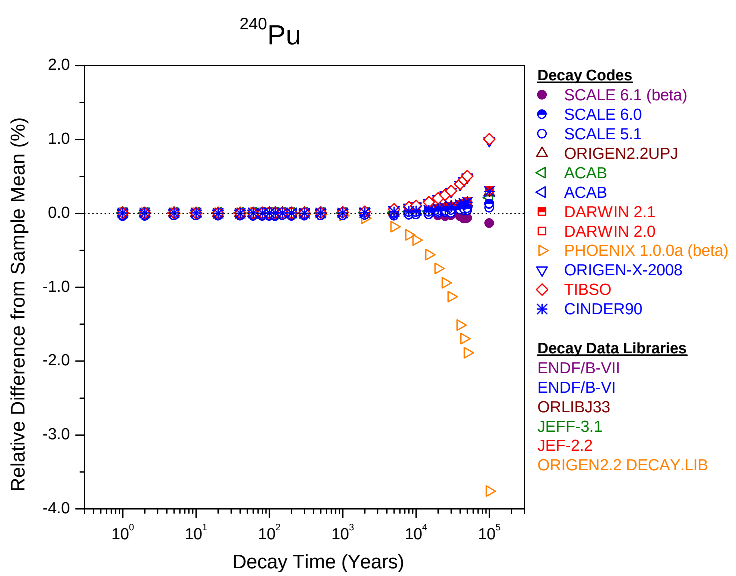
^{240}Pu is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $6.561\times10^3 \pm 7$ years and decays by alpha-particle emission and spontaneous fission [20]. The ^{240}Pu half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 80. A small ^{240}Pu quantity is produced from the ^{244}Cm alpha decay ($T_{1/2}$ = 18.1 ± 0.1 years), which represents approximately 3% of the total ^{240}Pu atom density at decay times greater than 100 years. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 81. In the table, the calculated ^{240}Pu atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{240}Pu using the evaluated decay codes/data libraries is illustrated in Figure 56. A very small dispersion of the calculated ^{240}Pu atom densities is observed at long decay times (e.g. RSD ≈ 1% at 10^6 years), which is consistent with the differences in the ^{240}Pu half-life values used.

Table 80. ^{240}Pu half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.07049E+11	2.07108E+11	2.07108E+11	2.07013E+11	2.07112E+11	2.06300E+11
Uncertainty (s)	2.209032+8	2.20899E+08	1.57785E+08	-	2.20903E+08	-

Sources: References 12–14, 20 and 21.

Figure 56. Relative difference from sample mean as a function of decay time for ^{240}Pu atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 81. Decay calculation results for ^{240}Pu (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	7.286E-05	0.00
1	7.291E-05	7.294E-05	7.294E-05	7.295E-05	7.294E-05	7.294E-05	7.294E-05	7.294E-05	7.294E-05	7.294E-05	7.294E-05	7.292E-05	7.294E-05	7.294E-05	7.294E-05	7.294E-05	0.01
2	7.299E-05	7.302E-05	7.302E-05	7.303E-05	7.302E-05	7.302E-05	7.302E-05	7.302E-05	7.302E-05	7.302E-05	7.302E-05	7.300E-05	7.302E-05	7.302E-05	7.302E-05	7.302E-05	0.01
5	7.321E-05	7.323E-05	7.323E-05	7.324E-05	7.323E-05	7.324E-05	7.323E-05	7.323E-05	7.323E-05	7.323E-05	7.323E-05	7.321E-05	7.323E-05	7.323E-05	7.323E-05	7.323E-05	0.01
10	7.351E-05	7.353E-05	7.353E-05	7.354E-05	7.353E-05	7.354E-05	7.353E-05	7.353E-05	7.353E-05	7.353E-05	7.353E-05	7.351E-05	7.353E-05	7.353E-05	7.353E-05	7.353E-05	0.01
20	7.394E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.397E-05	7.395E-05	7.397E-05	7.397E-05	7.397E-05	7.396E-05	0.01
40	7.437E-05	7.440E-05	7.440E-05	7.440E-05	7.440E-05	7.440E-05	7.440E-05	7.440E-05	7.439E-05	7.440E-05	7.440E-05	7.438E-05	7.440E-05	7.440E-05	7.440E-05	7.439E-05	0.01
60	7.448E-05	7.451E-05	7.451E-05	7.452E-05	7.451E-05	7.451E-05	7.451E-05	7.451E-05	7.451E-05	7.451E-05	7.451E-05	7.449E-05	7.451E-05	7.451E-05	7.451E-05	7.451E-05	0.01
80	7.445E-05	7.448E-05	7.448E-05	7.449E-05	7.448E-05	7.448E-05	7.448E-05	7.448E-05	7.448E-05	7.448E-05	7.448E-05	7.446E-05	7.448E-05	7.448E-05	7.448E-05	7.448E-05	0.01
100	7.435E-05	7.438E-05	7.438E-05	7.439E-05	7.438E-05	7.438E-05	7.438E-05	7.438E-05	7.438E-05	7.438E-05	7.438E-05	7.436E-05	7.438E-05	7.438E-05	7.438E-05	7.438E-05	0.01
120	7.422E-05	7.425E-05	7.425E-05	7.426E-05	7.425E-05	7.425E-05	7.425E-05	7.425E-05	7.425E-05	7.425E-05	7.425E-05	7.423E-05	7.425E-05	7.425E-05	7.425E-05	7.425E-05	0.01
150	7.401E-05	7.403E-05	7.403E-05	7.404E-05	7.403E-05	7.403E-05	7.403E-05	7.403E-05	7.403E-05	7.403E-05	7.403E-05	7.401E-05	7.403E-05	7.403E-05	7.403E-05	7.403E-05	0.01
200	7.362E-05	7.365E-05	7.365E-05	7.366E-05	7.365E-05	7.365E-05	7.365E-05	7.365E-05	7.364E-05	7.365E-05	7.365E-05	7.363E-05	7.365E-05	7.365E-05	7.365E-05	7.365E-05	0.01
300	7.285E-05	7.288E-05	7.288E-05	7.288E-05	7.288E-05	7.288E-05	7.288E-05	7.288E-05	7.287E-05	7.288E-05	7.288E-05	7.286E-05	7.288E-05	7.288E-05	7.288E-05	7.287E-05	0.01
500	7.133E-05	7.135E-05	7.135E-05	7.136E-05	7.135E-05	7.135E-05	7.135E-05	7.135E-05	7.134E-05	7.136E-05	7.135E-05	7.133E-05	7.135E-05	7.136E-05	7.135E-05	7.135E-05	0.01
1 000	6.766E-05	6.768E-05	6.768E-05	6.769E-05	6.768E-05	6.768E-05	6.768E-05	6.768E-05	6.766E-05	6.769E-05	6.768E-05	6.766E-05	6.768E-05	6.769E-05	6.768E-05	6.768E-05	0.02
2 000	6.088E-05	6.089E-05	6.090E-05	6.090E-05	6.090E-05	6.090E-05	6.090E-05	6.090E-05	6.085E-05	6.091E-05	6.090E-05	6.088E-05	6.090E-05	6.091E-05	6.090E-05	6.089E-05	0.02
5 000	4.434E-05	4.435E-05	4.436E-05	4.436E-05	4.436E-05	4.436E-05	4.436E-05	4.436E-05	4.427E-05	4.438E-05	4.436E-05	4.435E-05	4.436E-05	4.438E-05	4.436E-05	4.435E-05	0.05
8 000	3.230E-05	3.230E-05	3.232E-05	3.231E-05	3.231E-05	3.231E-05	3.232E-05	3.232E-05	3.221E-05	3.233E-05	3.231E-05	3.230E-05	3.231E-05	3.233E-05	3.232E-05	3.231E-05	0.09
10 000	2.615E-05	2.615E-05	2.616E-05	2.616E-05	2.616E-05	2.616E-05	2.616E-05	2.616E-05	2.606E-05	2.618E-05	2.616E-05	2.615E-05	2.616E-05	2.618E-05	2.616E-05	2.615E-05	0.11
15 000	1.542E-05	1.542E-05	1.543E-05	1.543E-05	1.543E-05	1.543E-05	1.543E-05	1.543E-05	1.534E-05	1.545E-05	1.543E-05	1.542E-05	1.543E-05	1.545E-05	1.543E-05	1.542E-05	0.16
20 000	9.093E-06	9.091E-06	9.099E-06	9.097E-06	9.098E-06	9.098E-06	9.100E-06	9.100E-06	9.026E-06	9.112E-06	9.096E-06	9.094E-06	9.096E-06	9.112E-06	9.099E-06	9.094E-06	0.22
25 000	5.362E-06	5.360E-06	5.366E-06	5.365E-06	5.365E-06	5.365E-06	5.366E-06	5.366E-06	5.312E-06	5.376E-06	5.364E-06	5.363E-06	5.364E-06	5.376E-06	5.366E-06	5.362E-06	0.27
30 000	3.162E-06	3.161E-06	3.165E-06	3.163E-06	3.164E-06	3.164E-06	3.165E-06	3.165E-06	3.126E-06	3.171E-06	3.163E-06	3.162E-06	3.163E-06	3.171E-06	3.165E-06	3.162E-06	0.33
40 000	1.100E-06	1.099E-06	1.101E-06	1.100E-06	1.100E-06	1.100E-06	1.101E-06	1.101E-06	1.083E-06	1.104E-06	1.100E-06	1.100E-06	1.100E-06	1.104E-06	1.101E-06	1.099E-06	0.44
45 000	6.484E-07	6.478E-07	6.491E-07	6.487E-07	6.489E-07	6.489E-07	6.492E-07	6.492E-07	6.372E-07	6.511E-07	6.487E-07	6.485E-07	6.487E-07	6.512E-07	6.491E-07	6.482E-07	0.49
50 000	3.824E-07	3.820E-07	3.828E-07	3.825E-07	3.827E-07	3.827E-07	3.828E-07	3.828E-07	3.750E-07	3.841E-07	3.825E-07	3.824E-07	3.825E-07	3.842E-07	3.828E-07	3.822E-07	0.55
100 000	1.944E-09	1.940E-09	1.948E-09	1.945E-09	1.947E-09	1.947E-09	1.949E-09	1.949E-09	1.870E-09	1.962E-09	1.945E-09	1.945E-09	1.945E-09	1.962E-09	1.948E-09	1.943E-09	1.09

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.41. Time-dependent ^{241}Pu atom densities

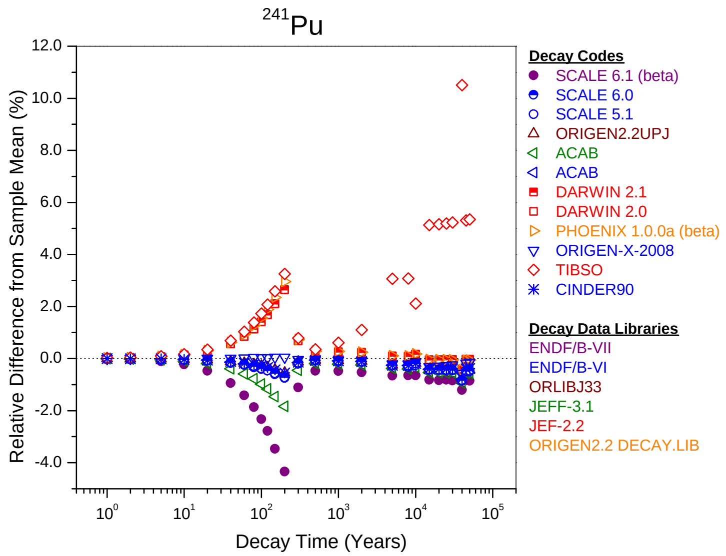
^{241}Pu is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of 14.29 ± 0.06 years and decays by beta- and alpha-particle emissions [20]. ^{245}Cm ($T_{1/2}$ = 8.5×10^3 ± 100 years) alpha decay is the only significant ^{241}Pu production path at long decay times. ^{241}Pu concentration decreases by more than five orders of magnitude during the first 300 years after fuel discharge, and very small ^{241}Pu quantities are formed as a result of ^{245}Cm alpha decay. The ^{241}Pu half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 82. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 83. In the table, the calculated ^{241}Pu atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{241}Pu using the evaluated decay codes/data libraries is illustrated in Figure 57. A dispersion of approximately 2% in the decay calculation results is observed at 200 years after fuel discharge due to different ^{241}Pu half-life values associated with the decay libraries. In addition, the ^{241}Pu atom density at 4×10^4 years after fuel discharge calculated using TIBSO is approximately 10% higher than the other results at that decay time.

Table 82. ^{241}Pu half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	4.50958E+08	4.52842E+08	4.52220E+08	4.54420E+08	4.52851E+08	4.54400E+08
Uncertainty (s)	1.89346E+05	3.15569E+06	1.26230E+06	-	3.15575E+08	-

Sources: References 12–14, 20 and 21.

Figure 57. Relative difference from sample mean as a function of decay time for ^{241}Pu atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 83. Decay calculation results for ^{241}Pu (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	4.799E-05	0.00
1	4.572E-05	4.572E-05	4.573E-05	4.573E-05	4.573E-05	4.573E-05	4.574E-05	4.574E-05	4.574E-05	4.573E-05	4.573E-05	4.572E-05	4.573E-05	4.574E-05	4.573E-05	4.573E-05	0.01
2	4.357E-05	4.356E-05	4.357E-05	4.358E-05	4.357E-05	4.357E-05	4.359E-05	4.359E-05	4.359E-05	4.358E-05	4.357E-05	4.356E-05	4.357E-05	4.359E-05	4.357E-05	4.358E-05	0.02
5	3.769E-05	3.766E-05	3.770E-05	3.770E-05	3.770E-05	3.768E-05	3.773E-05	3.773E-05	3.773E-05	3.770E-05	3.769E-05	3.768E-05	3.769E-05	3.773E-05	3.770E-05	3.770E-05	0.06
10	2.960E-05	2.955E-05	2.961E-05	2.961E-05	2.961E-05	2.959E-05	2.966E-05	2.966E-05	2.966E-05	2.962E-05	2.961E-05	2.960E-05	2.961E-05	2.967E-05	2.961E-05	2.962E-05	0.11
20	1.826E-05	1.819E-05	1.827E-05	1.826E-05	1.826E-05	1.824E-05	1.833E-05	1.833E-05	1.833E-05	1.828E-05	1.826E-05	1.826E-05	1.826E-05	1.834E-05	1.827E-05	1.828E-05	0.22
40	6.948E-06	6.894E-06	6.952E-06	6.950E-06	6.950E-06	6.932E-06	6.999E-06	6.999E-06	7.003E-06	6.961E-06	6.949E-06	6.947E-06	6.949E-06	7.008E-06	6.952E-06	6.959E-06	0.44
60	2.644E-06	2.613E-06	2.646E-06	2.645E-06	2.645E-06	2.635E-06	2.673E-06	2.673E-06	2.675E-06	2.651E-06	2.644E-06	2.644E-06	2.644E-06	2.678E-06	2.646E-06	2.650E-06	0.66
80	1.006E-06	9.905E-07	1.007E-06	1.006E-06	1.007E-06	1.002E-06	1.021E-06	1.021E-06	1.022E-06	1.010E-06	1.006E-06	1.006E-06	1.006E-06	1.023E-06	1.007E-06	1.009E-06	0.88
100	3.830E-07	3.756E-07	3.834E-07	3.831E-07	3.832E-07	3.808E-07	3.900E-07	3.900E-07	3.906E-07	3.847E-07	3.831E-07	3.830E-07	3.831E-07	3.912E-07	3.834E-07	3.845E-07	1.10
120	1.459E-07	1.425E-07	1.461E-07	1.459E-07	1.460E-07	1.449E-07	1.491E-07	1.491E-07	1.493E-07	1.466E-07	1.459E-07	1.459E-07	1.459E-07	1.496E-07	1.461E-07	1.466E-07	1.31
150	3.442E-08	3.342E-08	3.447E-08	3.443E-08	3.445E-08	3.412E-08	3.535E-08	3.535E-08	3.544E-08	3.464E-08	3.442E-08	3.441E-08	3.442E-08	3.552E-08	3.447E-08	3.462E-08	1.64
200	3.285E-09	3.166E-09	3.292E-09	3.286E-09	3.288E-09	3.249E-09	3.397E-09	3.397E-09	3.408E-09	3.311E-09	3.286E-09	3.285E-09	3.286E-09	3.418E-09	3.292E-09	3.310E-09	2.06
300	2.546E-10	2.522E-10	2.547E-10	2.546E-10	2.546E-10	2.539E-10	2.567E-10	2.567E-10	2.569E-10	2.549E-10	2.546E-10	2.545E-10	2.546E-10	2.570E-10	2.547E-10	2.550E-10	0.51
500	2.265E-10	2.256E-10	2.265E-10	2.266E-10	2.265E-10	2.262E-10	2.273E-10	2.273E-10	2.273E-10	2.266E-10	2.265E-10	2.265E-10	2.265E-10	2.275E-10	2.265E-10	2.267E-10	0.22
1 000	2.175E-10	2.166E-10	2.175E-10	2.175E-10	2.175E-10	2.172E-10	2.182E-10	2.182E-10	2.183E-10	2.175E-10	2.175E-10	2.174E-10	2.175E-10	2.190E-10	2.175E-10	2.176E-10	0.26
2 000	2.004E-10	1.996E-10	2.005E-10	2.004E-10	2.004E-10	2.002E-10	2.011E-10	2.011E-10	2.012E-10	2.005E-10	2.004E-10	2.004E-10	2.004E-10	2.029E-10	2.004E-10	2.007E-10	0.36
5 000	1.569E-10	1.563E-10	1.570E-10	1.569E-10	1.569E-10	1.567E-10	1.575E-10	1.575E-10	1.575E-10	1.570E-10	1.569E-10	1.569E-10	1.569E-10	1.622E-10	1.569E-10	1.573E-10	0.87
8 000	1.229E-10	1.224E-10	1.229E-10	1.229E-10	1.229E-10	1.227E-10	1.233E-10	1.233E-10	1.233E-10	1.229E-10	1.229E-10	1.228E-10	1.229E-10	1.270E-10	1.229E-10	1.232E-10	0.87
10 000	1.044E-10	1.039E-10	1.044E-10	1.044E-10	1.044E-10	1.042E-10	1.048E-10	1.048E-10	1.048E-10	1.045E-10	1.044E-10	1.043E-10	1.044E-10	1.068E-10	1.044E-10	1.046E-10	0.62
15 000	6.942E-11	6.914E-11	6.943E-11	6.942E-11	6.942E-11	6.933E-11	6.968E-11	6.968E-11	6.968E-11	6.949E-11	6.942E-11	6.940E-11	6.942E-11	7.329E-11	6.943E-11	6.971E-11	1.43
20 000	4.617E-11	4.598E-11	4.618E-11	4.617E-11	4.618E-11	4.611E-11	4.635E-11	4.635E-11	4.635E-11	4.623E-11	4.617E-11	4.616E-11	4.617E-11	4.876E-11	4.618E-11	4.637E-11	1.44
25 000	3.071E-11	3.059E-11	3.072E-11	3.071E-11	3.071E-11	3.067E-11	3.083E-11	3.083E-11	3.083E-11	3.076E-11	3.071E-11	3.070E-11	3.071E-11	3.244E-11	3.072E-11	3.084E-11	1.45
30 000	2.042E-11	2.034E-11	2.043E-11	2.042E-11	2.043E-11	2.040E-11	2.051E-11	2.051E-11	2.050E-11	2.046E-11	2.042E-11	2.042E-11	2.042E-11	2.159E-11	2.043E-11	2.051E-11	1.46
40 000	9.035E-12	9.000E-12	9.037E-12	9.035E-12	9.036E-12	9.024E-12	9.073E-12	9.073E-12	9.070E-12	9.058E-12	9.034E-12	9.032E-12	9.034E-12	1.007E-11	9.040E-12	9.110E-12	2.92
45 000	6.009E-12	5.986E-12	6.011E-12	6.009E-12	6.010E-12	6.002E-12	6.035E-12	6.035E-12	6.033E-12	6.026E-12	6.009E-12	6.007E-12	6.009E-12	6.357E-12	6.013E-12	6.037E-12	1.49
50 000	3.996E-12	3.981E-12	3.998E-12	3.996E-12	3.998E-12	3.992E-12	4.014E-12	4.014E-12	4.013E-12	4.009E-12	3.996E-12	3.995E-12	3.996E-12	4.230E-12	4.000E-12	4.015E-12	1.50

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.42. Time-dependent ^{242}Pu atom densities

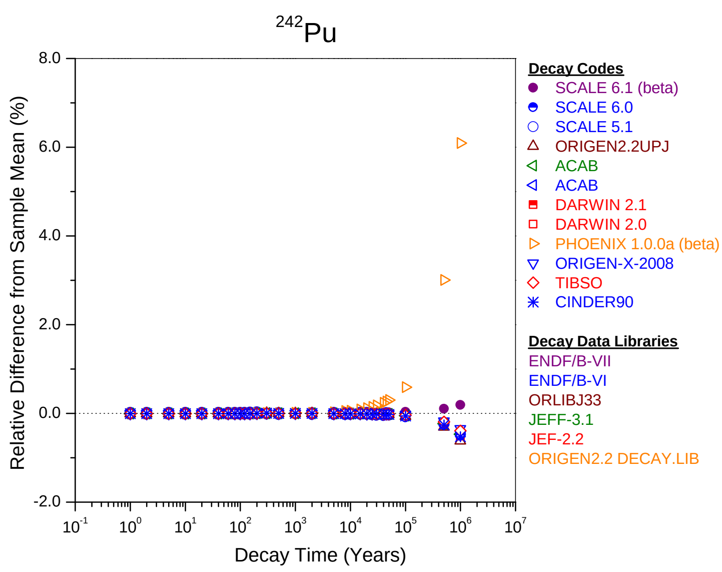
^{242}Pu is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $3.75\times10^5 \pm 2\times10^3$ years and decays by alpha-particle emission and spontaneous fission [20]. The ^{242}Pu half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 84. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 85. In the table, the calculated ^{242}Pu atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{242}Pu using the evaluated decay codes/data libraries is illustrated in Figure 58. As seen in the figure, PHOENIX 1.0.0a (beta) predicts slightly higher ^{242}Pu concentrations than the other evaluated codes/libraries (e.g. ~6% higher at 10^6 years) at very long decay times as a result of a higher ^{242}Pu half-life value used.

Table 84. ^{242}Pu half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.18340E+13	1.17865E+13	1.17868E+13	1.18023E+13	1.17804E+13	1.22100E+13
Uncertainty (s)	6.31152E+10	3.47126E+10	3.47134E+10	-	3.78691E+10	-

Sources: References 12–14, 20 and 21.

Figure 58. Relative difference from sample mean as a function of decay time for ^{242}Pu atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 85. Decay calculation results for ^{242}Pu (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.00
1	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
2	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
5	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
10	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
20	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
40	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
60	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
80	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
100	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
120	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
150	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	0.01
200	1.901E-05	1.900E-05	1.900E-05	1.901E-05	1.901E-05	1.900E-05	1.901E-05	1.901E-05	1.901E-05	1.901E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	0.02
300	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	0.01
500	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	1.899E-05	1.900E-05	1.900E-05	1.900E-05	1.900E-05	0.01
1 000	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	1.898E-05	0.00
2 000	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	1.894E-05	1.895E-05	1.895E-05	1.895E-05	1.895E-05	0.01
5 000	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	1.884E-05	1.885E-05	1.885E-05	1.885E-05	1.885E-05	0.02
8 000	1.874E-05	1.875E-05	1.874E-05	1.875E-05	1.874E-05	1.874E-05	1.874E-05	1.874E-05	1.875E-05	1.874E-05	1.874E-05	1.874E-05	1.874E-05	1.874E-05	1.874E-05	1.874E-05	0.02
10 000	1.868E-05	1.868E-05	1.868E-05	1.868E-05	1.868E-05	1.868E-05	1.868E-05	1.868E-05	1.869E-05	1.868E-05	1.868E-05	1.867E-05	1.868E-05	1.868E-05	1.868E-05	1.868E-05	0.02
15 000	1.851E-05	1.851E-05	1.850E-05	1.851E-05	1.851E-05	1.851E-05	1.851E-05	1.851E-05	1.852E-05	1.851E-05	1.850E-05	1.850E-05	1.850E-05	1.851E-05	1.850E-05	1.851E-05	0.03
20 000	1.834E-05	1.834E-05	1.833E-05	1.834E-05	1.834E-05	1.834E-05	1.834E-05	1.834E-05	1.836E-05	1.834E-05	1.833E-05	1.833E-05	1.833E-05	1.834E-05	1.833E-05	1.834E-05	0.04
25 000	1.817E-05	1.817E-05	1.817E-05	1.817E-05	1.817E-05	1.817E-05	1.817E-05	1.817E-05	1.820E-05	1.817E-05	1.817E-05	1.816E-05	1.817E-05	1.817E-05	1.817E-05	1.817E-05	0.04
30 000	1.800E-05	1.800E-05	1.800E-05	1.800E-05	1.800E-05	1.800E-05	1.800E-05	1.800E-05	1.803E-05	1.800E-05	1.800E-05	1.799E-05	1.800E-05	1.800E-05	1.800E-05	1.800E-05	0.05
40 000	1.767E-05	1.767E-05	1.767E-05	1.767E-05	1.767E-05	1.767E-05	1.767E-05	1.767E-05	1.771E-05	1.767E-05	1.767E-05	1.766E-05	1.767E-05	1.767E-05	1.767E-05	1.767E-05	0.07
45 000	1.751E-05	1.751E-05	1.750E-05	1.751E-05	1.751E-05	1.750E-05	1.750E-05	1.750E-05	1.756E-05	1.751E-05	1.750E-05	1.750E-05	1.750E-05	1.751E-05	1.750E-05	1.751E-05	0.08
50 000	1.734E-05	1.735E-05	1.734E-05	1.734E-05	1.734E-05	1.734E-05	1.734E-05	1.734E-05	1.740E-05	1.734E-05	1.734E-05	1.734E-05	1.734E-05	1.734E-05	1.734E-05	1.735E-05	0.08
100 000	1.581E-05	1.582E-05	1.580E-05	1.581E-05	1.581E-05	1.581E-05	1.581E-05	1.581E-05	1.591E-05	1.581E-05	1.581E-05	1.580E-05	1.581E-05	1.581E-05	1.581E-05	1.581E-05	0.17
500 000	7.525E-06	7.551E-06	7.520E-06	7.526E-06	7.526E-06	7.525E-06	7.524E-06	7.524E-06	7.770E-06	7.530E-06	7.525E-06	7.523E-06	7.525E-06	7.529E-06	7.523E-06	7.543E-06	0.84
1 000 000	2.976E-06	2.996E-06	2.972E-06	2.976E-06	2.976E-06	2.976E-06	2.975E-06	2.975E-06	3.173E-06	2.980E-06	2.976E-06	2.975E-06	2.976E-06	2.979E-06	2.974E-06	2.990E-06	1.70

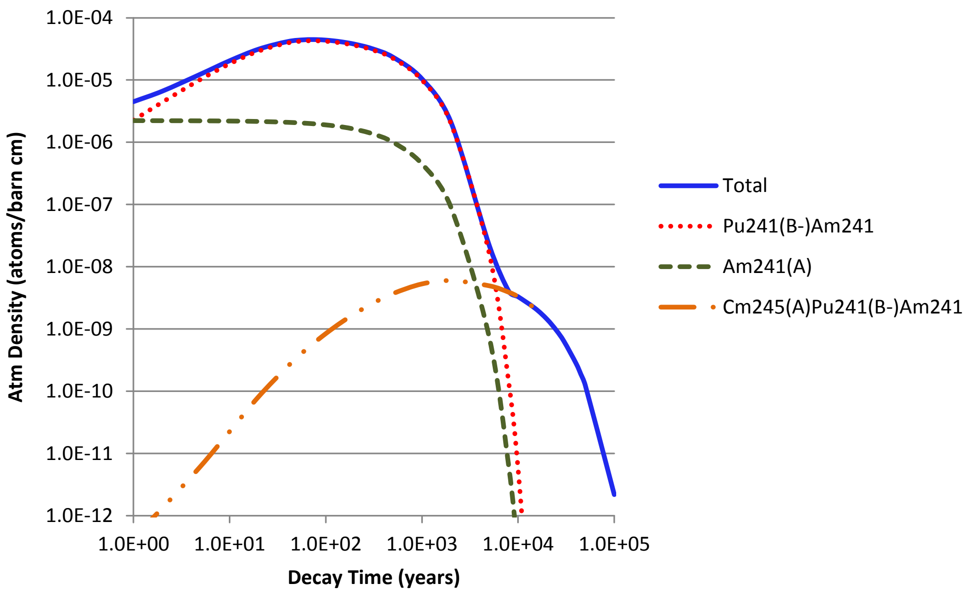
[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.43. Time-dependent ^{241}Am atom densities

^{241}Am is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of 432.6 ± 0.6 years and decays by alpha-particle emission and spontaneous fission [20]. ^{241}Am atom density as a function of decay time and the contributions from the primary decay chains resulting in the formation of the ^{241}Am nuclide are illustrated in Figure 59. As seen in the figure, ^{241}Am concentrations increase after fuel discharge reaching a maximum value at approximately 100 years as a result of ^{241}Pu beta decay ($T_{1/2}$ = 14.29 ± 0.06 years; branching ratio = 99.998%). Very small ^{241}Am quantities are formed as a result of ^{245}Cm alpha decay.

Figure 59. ^{241}Am atom density as a function of decay time



Note: Representative PWR spent fuel of 4.5 wt% ^{235}U initial enrichment and 50 GWd/MTU burn-up; A denotes alpha decay; B- denotes beta decay.

The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 86. In the table, the calculated ^{241}Am atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{241}Am using the evaluated decay codes/data libraries is illustrated in Figure 60. As seen in the figure, there is a significant dispersion of the decay calculation results at long decay times (e.g. RSD ≈ 18% at 10^5). The ^{241}Am half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 87. The values of ^{241}Pu branching ratio for beta decay in those libraries are also indicated in the table. The half-life values for ^{241}Pu and ^{245}Cm are presented in Table 82 and Table 92, respectively.

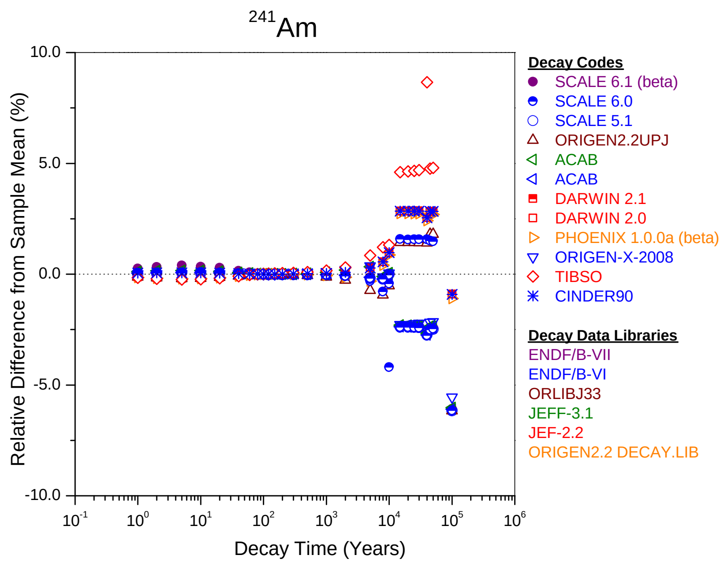
Table 86. Decay calculation results for ^{241}Am (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	2.231E-06	0.00
1	4.487E-06	4.498E-06	4.481E-06	4.490E-06	4.489E-06	4.492E-06	4.481E-06	4.481E-06	4.480E-06	4.487E-06	4.489E-06	4.488E-06	4.489E-06	4.480E-06	4.489E-06	4.487E-06	0.12
2	6.635E-06	6.654E-06	6.622E-06	6.638E-06	6.637E-06	6.642E-06	6.622E-06	6.622E-06	6.620E-06	6.634E-06	6.637E-06	6.635E-06	6.637E-06	6.619E-06	6.636E-06	6.633E-06	0.15
5	1.247E-05	1.251E-05	1.244E-05	1.247E-05	1.247E-05	1.248E-05	1.244E-05	1.244E-05	1.244E-05	1.246E-05	1.247E-05	1.247E-05	1.247E-05	1.243E-05	1.247E-05	1.246E-05	0.18
10	2.042E-05	2.048E-05	2.037E-05	2.043E-05	2.043E-05	2.044E-05	2.037E-05	2.037E-05	2.037E-05	2.041E-05	2.043E-05	2.042E-05	2.043E-05	2.036E-05	2.042E-05	2.041E-05	0.16
20	3.134E-05	3.142E-05	3.128E-05	3.135E-05	3.135E-05	3.137E-05	3.128E-05	3.128E-05	3.128E-05	3.133E-05	3.135E-05	3.134E-05	3.135E-05	3.127E-05	3.134E-05	3.133E-05	0.13
40	4.146E-05	4.151E-05	4.142E-05	4.147E-05	4.146E-05	4.148E-05	4.142E-05	4.142E-05	4.141E-05	4.146E-05	4.146E-05	4.145E-05	4.146E-05	4.141E-05	4.146E-05	4.145E-05	0.07
60	4.437E-05	4.441E-05	4.436E-05	4.438E-05	4.438E-05	4.439E-05	4.436E-05	4.436E-05	4.435E-05	4.438E-05	4.438E-05	4.437E-05	4.438E-05	4.436E-05	4.438E-05	4.437E-05	0.04
80	4.458E-05	4.460E-05	4.458E-05	4.459E-05	4.459E-05	4.460E-05	4.458E-05	4.458E-05	4.458E-05	4.459E-05	4.459E-05	4.458E-05	4.459E-05	4.459E-05	4.459E-05	4.459E-05	0.02
100	4.379E-05	4.380E-05	4.379E-05	4.380E-05	4.380E-05	4.380E-05	4.380E-05	4.380E-05	4.379E-05	4.380E-05	4.380E-05	4.378E-05	4.380E-05	4.380E-05	4.380E-05	4.380E-05	0.01
120	4.264E-05	4.264E-05	4.264E-05	4.265E-05	4.265E-05	4.265E-05	4.265E-05	4.265E-05	4.265E-05	4.265E-05	4.265E-05	4.263E-05	4.265E-05	4.266E-05	4.265E-05	4.265E-05	0.02
150	4.075E-05	4.075E-05	4.075E-05	4.076E-05	4.075E-05	4.076E-05	4.076E-05	4.076E-05	4.076E-05	4.076E-05	4.075E-05	4.074E-05	4.075E-05	4.077E-05	4.076E-05	4.076E-05	0.02
200	3.764E-05	3.764E-05	3.764E-05	3.765E-05	3.765E-05	3.765E-05	3.765E-05	3.765E-05	3.765E-05	3.766E-05	3.765E-05	3.763E-05	3.765E-05	3.766E-05	3.765E-05	3.765E-05	0.02
300	3.207E-05	3.207E-05	3.207E-05	3.208E-05	3.208E-05	3.209E-05	3.208E-05	3.208E-05	3.208E-05	3.209E-05	3.207E-05	3.207E-05	3.207E-05	3.210E-05	3.208E-05	3.208E-05	0.03
500	2.328E-05	2.328E-05	2.327E-05	2.328E-05	2.328E-05	2.329E-05	2.329E-05	2.329E-05	2.328E-05	2.330E-05	2.328E-05	2.327E-05	2.328E-05	2.331E-05	2.329E-05	2.328E-05	0.04
1 000	1.045E-05	1.045E-05	1.044E-05	1.045E-05	1.045E-05	1.046E-05	1.046E-05	1.046E-05	1.045E-05	1.047E-05	1.045E-05	1.045E-05	1.045E-05	1.047E-05	1.046E-05	1.045E-05	0.07
2 000	2.109E-06	2.110E-06	2.105E-06	2.109E-06	2.110E-06	2.115E-06	2.113E-06	2.113E-06	2.108E-06	2.115E-06	2.109E-06	2.109E-06	2.109E-06	2.117E-06	2.113E-06	2.111E-06	0.15
5 000	2.212E-08	2.213E-08	2.200E-08	2.212E-08	2.213E-08	2.223E-08	2.222E-08	2.222E-08	2.209E-08	2.224E-08	2.209E-08	2.211E-08	2.212E-08	2.235E-08	2.222E-08	2.216E-08	0.39
8 000	4.014E-09	4.014E-09	3.985E-09	4.014E-09	4.014E-09	4.018E-09	4.045E-09	4.045E-09	4.039E-09	4.018E-09	3.991E-09	4.013E-09	4.014E-09	4.072E-09	4.045E-09	4.023E-09	0.56
10 000	3.290E-09	3.290E-09	3.273E-09	3.290E-09	3.290E-09	3.292E-09	3.322E-09	3.322E-09	3.319E-09	3.292E-09	3.276E-09	3.289E-09	3.152E-09	3.334E-09	3.322E-09	3.290E-09	1.29
15 000	2.094E-09	2.094E-09	2.176E-09	2.094E-09	2.094E-09	2.096E-09	2.206E-09	2.206E-09	2.204E-09	2.096E-09	2.179E-09	2.093E-09	2.094E-09	2.244E-09	2.206E-09	2.145E-09	2.70
20 000	1.393E-09	1.393E-09	1.447E-09	1.393E-09	1.393E-09	1.394E-09	1.467E-09	1.467E-09	1.466E-09	1.394E-09	1.449E-09	1.392E-09	1.393E-09	1.493E-09	1.467E-09	1.427E-09	2.71
25 000	9.262E-10	9.264E-10	9.625E-10	9.262E-10	9.263E-10	9.270E-10	9.760E-10	9.760E-10	9.749E-10	9.277E-10	9.639E-10	9.259E-10	9.262E-10	9.932E-10	9.760E-10	9.490E-10	2.71
30 000	6.160E-10	6.162E-10	6.402E-10	6.160E-10	6.161E-10	6.166E-10	6.492E-10	6.492E-10	6.484E-10	6.172E-10	6.411E-10	6.158E-10	6.160E-10	6.608E-10	6.492E-10	6.312E-10	2.72
40 000	2.724E-10	2.724E-10	2.840E-10	2.724E-10	2.724E-10	2.726E-10	2.872E-10	2.872E-10	2.869E-10	2.731E-10	2.845E-10	2.723E-10	2.723E-10	3.044E-10	2.872E-10	2.801E-10	3.42
45 000	1.812E-10	1.813E-10	1.891E-10	1.812E-10	1.813E-10	1.814E-10	1.911E-10	1.911E-10	1.908E-10	1.818E-10	1.886E-10	1.812E-10	1.811E-10	1.946E-10	1.910E-10	1.858E-10	2.75
50 000	1.205E-10	1.206E-10	1.258E-10	1.205E-10	1.206E-10	1.207E-10	1.271E-10	1.271E-10	1.269E-10	1.209E-10	1.254E-10	1.205E-10	1.205E-10	1.295E-10	1.271E-10	1.236E-10	2.76
100 000	2.040E-12	2.042E-12	2.040E-12	2.041E-12	2.042E-12	2.043E-12	2.155E-12	2.155E-12	2.150E-12	2.054E-12	2.040E-12	2.040E-12	2.040E-12	3.576E-12	2.154E-12	2.174E-12	17.99

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

Figure 60. Relative difference from sample mean as a function of decay time for ^{241}Am atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 87. ^{241}Am half-life and associated uncertainty values and ^{241}Pu branching ratio for beta decay

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.36518E+10	1.36547E+10	1.36581E+10	1.36547E+10	1.36400E+10
Uncertainty (s)	1.893456E+07	1.57785E+07	2.20903E+07	-	-
^{241}Pu branching ratio for beta decay	9.999755E-01	9.999761E-01	9.999750E-01	9.999800E-01	9.999755E-01

Sources: References 12, 13, 20 and 21.

3.44. Time-dependent ^{242m}Am atom densities

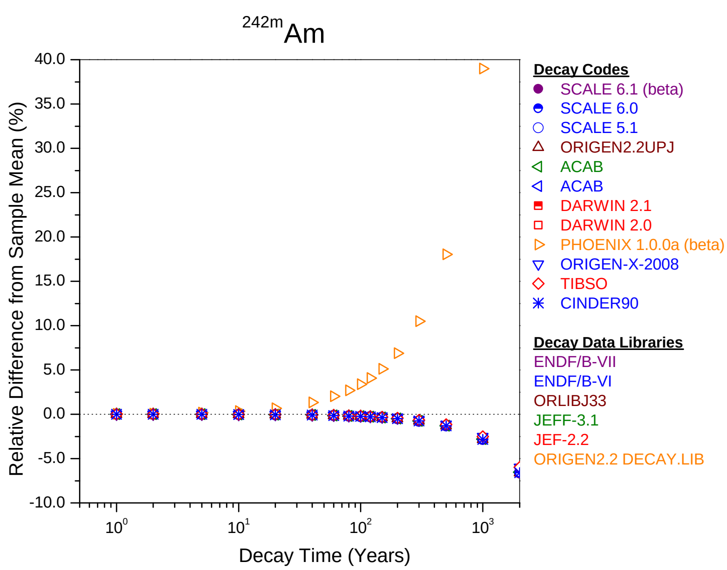
^{242m}Am is a metastable isomer important for burn-up credit criticality safety analyses and for radiological dose assessments. The ^{242m}Am isomer has a half-life of 141 ± 2 years and decays by isomeric transition and by alpha-particle decay [20]. The ^{242m}Am half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 88. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 89. In the table, the calculated ^{242m}Am atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{242m}Am using the evaluated decay codes/data libraries is illustrated in Figure 61. As seen in the figure, PHOENIX 1.0.0a (beta) predicts higher ^{242m}Am concentrations at long decay times than the other evaluated codes/libraries (e.g. ~ 40% higher at 10^3 years) due to a greater ^{242m}Am half-life value in the ORIGEN2.2 DECAY.LIB library than in the other decay data libraries.

Table 88. ^{242m}Am half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	4.44962E+09	4.44953E+09	4.44962E+09	4.44962E+09	4.44962E+09	4.79700E+09
Uncertainty (s)	6.31152E+07	6.31139E+07	6.31152E+07	-	6.31152E+07	-

Sources: References 12–14, 20 and 21.

Figure 61. Relative difference from sample mean as a function of decay time for ^{242m}Am atom density



Note: For a decay code using multiple sources of decay data, only the primary decay data source is indicated in the figure.

Table 89. Decay calculation results for ^{242m}Am (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	5.263E-08	0.00
1	5.237E-08	5.237E-08	5.237E-08	5.238E-08	5.237E-08	5.237E-08	5.237E-08	5.237E-08	5.239E-08	5.237E-08	5.237E-08	5.236E-08	5.237E-08	5.237E-08	5.237E-08	5.237E-08	0.01
2	5.212E-08	5.212E-08	5.212E-08	5.212E-08	5.212E-08	5.212E-08	5.212E-08	5.212E-08	5.215E-08	5.212E-08	5.212E-08	5.210E-08	5.212E-08	5.212E-08	5.212E-08	5.212E-08	0.02
5	5.135E-08	5.135E-08	5.135E-08	5.136E-08	5.135E-08	5.135E-08	5.135E-08	5.135E-08	5.144E-08	5.135E-08	5.135E-08	5.134E-08	5.135E-08	5.135E-08	5.135E-08	5.136E-08	0.05
10	5.011E-08	5.011E-08	5.011E-08	5.011E-08	5.011E-08	5.011E-08	5.011E-08	5.011E-08	5.029E-08	5.011E-08	5.011E-08	5.009E-08	5.011E-08	5.011E-08	5.011E-08	5.012E-08	0.09
20	4.770E-08	4.770E-08	4.770E-08	4.770E-08	4.770E-08	4.770E-08	4.770E-08	4.770E-08	4.804E-08	4.771E-08	4.770E-08	4.769E-08	4.770E-08	4.771E-08	4.770E-08	4.772E-08	0.19
40	4.324E-08	4.323E-08	4.323E-08	4.324E-08	4.324E-08	4.324E-08	4.324E-08	4.324E-08	4.386E-08	4.324E-08	4.323E-08	4.322E-08	4.324E-08	4.324E-08	4.323E-08	4.328E-08	0.37
60	3.919E-08	3.919E-08	3.919E-08	3.919E-08	3.919E-08	3.919E-08	3.919E-08	3.919E-08	4.004E-08	3.919E-08	3.919E-08	3.918E-08	3.919E-08	3.919E-08	3.919E-08	3.924E-08	0.56
80	3.552E-08	3.552E-08	3.552E-08	3.552E-08	3.552E-08	3.552E-08	3.552E-08	3.552E-08	3.655E-08	3.553E-08	3.552E-08	3.551E-08	3.552E-08	3.553E-08	3.552E-08	3.559E-08	0.75
100	3.219E-08	3.219E-08	3.219E-08	3.219E-08	3.219E-08	3.219E-08	3.219E-08	3.219E-08	3.336E-08	3.220E-08	3.219E-08	3.218E-08	3.219E-08	3.220E-08	3.219E-08	3.227E-08	0.94
120	2.918E-08	2.918E-08	2.918E-08	2.918E-08	2.918E-08	2.918E-08	2.918E-08	2.918E-08	3.046E-08	2.919E-08	2.918E-08	2.917E-08	2.918E-08	2.919E-08	2.918E-08	2.926E-08	1.13
150	2.518E-08	2.517E-08	2.518E-08	2.518E-08	2.518E-08	2.518E-08	2.518E-08	2.518E-08	2.657E-08	2.519E-08	2.518E-08	2.517E-08	2.518E-08	2.519E-08	2.518E-08	2.527E-08	1.42
200	1.969E-08	1.969E-08	1.969E-08	1.969E-08	1.969E-08	1.969E-08	1.969E-08	1.969E-08	2.115E-08	1.970E-08	1.969E-08	1.969E-08	1.969E-08	1.970E-08	1.969E-08	1.979E-08	1.90
300	1.204E-08	1.204E-08	1.204E-08	1.204E-08	1.205E-08	1.205E-08	1.204E-08	1.204E-08	1.341E-08	1.206E-08	1.204E-08	1.204E-08	1.204E-08	1.206E-08	1.204E-08	1.214E-08	2.90
500	4.506E-09	4.504E-09	4.506E-09	4.506E-09	4.507E-09	4.507E-09	4.506E-09	4.506E-09	5.389E-09	4.513E-09	4.506E-09	4.505E-09	4.506E-09	4.513E-09	4.506E-09	4.566E-09	4.99
1 000	3.857E-10	3.855E-10	3.857E-10	3.858E-10	3.859E-10	3.859E-10	3.858E-10	3.858E-10	5.517E-10	3.870E-10	3.857E-10	3.856E-10	3.857E-10	3.870E-10	3.857E-10	3.970E-10	10.79
2 000	2.827E-12	2.824E-12	2.827E-12	2.827E-12	2.829E-12	2.829E-12	2.827E-12	2.827E-12	5.784E-12	2.845E-12	2.827E-12	2.826E-12	2.827E-12	2.846E-12	2.827E-12	3.027E-12	25.20

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.45. Time-dependent ^{243}Am atom densities

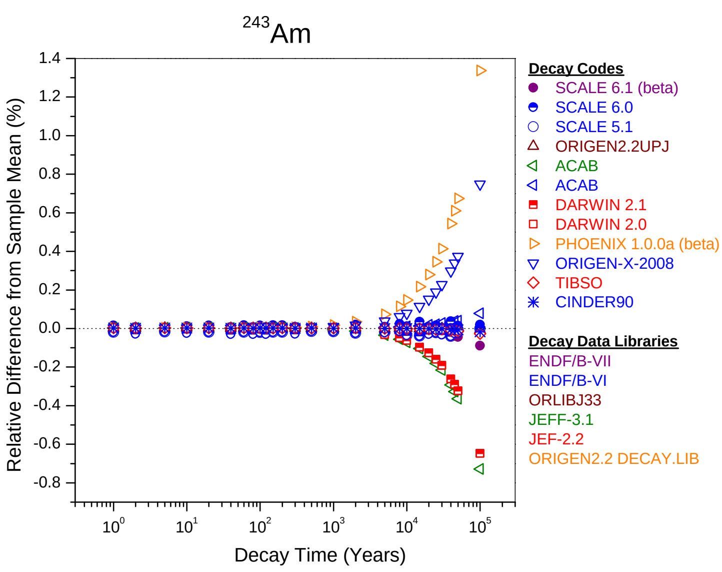
^{243}Am is an actinide nuclide important for burn-up credit criticality safety analyses and for radiological dose assessments. This nuclide has a half-life of $7.370 \times 10^3 \pm 40$ years and decays by alpha-particle emission and spontaneous fission [20]. The ^{243}Am half-life values and the uncertainties associated with the half-life values in the in ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, ORIGEN2.2-UPJ ORLIBJ33, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 90. The parent nuclide ^{243}Pu ($T_{1/2} = 4.956$ hours) completely decays to form a very small fraction (~ 0.1%) of the ^{243}Am total density. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 91. In the table, the calculated ^{243}Am atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{243}Am using the evaluated decay codes/data libraries is illustrated in Figure 62. A very small dispersion of the decay calculation results is observed at long decay times (e.g. RSD ≈ 0.5% at 10^5 years).

Table 90. ^{243}Am half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2-UPJ ORLIBJ33	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.32579E+11	2.32575E+11	2.32416E+11	2.32259E+11	2.32579E+11	2.32900E+11
Uncertainty (s)	1.26230E+09	4.73354E+08	6.91200E+08	-	1.26230E+09	-

Sources: References 12–14, 20 and 21.

Figure 62. Relative difference from sample mean as a function of decay time for ^{243}Am atom density



Note: For a decay code using multiple sources of decay data, only the primary decay data source is indicated in the figure.

Table 91. Decay calculation results for ^{243}Am (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	0.00
1	5.612E-06	5.613E-06	5.613E-06	5.614E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.612E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	0.01
2	5.612E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	5.611E-06	5.613E-06	5.613E-06	5.613E-06	5.613E-06	0.01
5	5.610E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	5.610E-06	5.611E-06	5.611E-06	5.611E-06	5.611E-06	0.01
10	5.608E-06	5.608E-06	5.608E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.609E-06	5.608E-06	5.607E-06	5.608E-06	5.608E-06	5.608E-06	5.608E-06	0.01
20	5.602E-06	5.603E-06	5.603E-06	5.604E-06	5.603E-06	5.603E-06	5.603E-06	5.603E-06	5.603E-06	5.603E-06	5.603E-06	5.602E-06	5.603E-06	5.603E-06	5.603E-06	5.603E-06	0.01
40	5.592E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	5.591E-06	5.593E-06	5.593E-06	5.593E-06	5.593E-06	0.01
60	5.581E-06	5.582E-06	5.582E-06	5.583E-06	5.582E-06	5.582E-06	5.582E-06	5.582E-06	5.582E-06	5.582E-06	5.582E-06	5.581E-06	5.582E-06	5.582E-06	5.582E-06	5.582E-06	0.01
80	5.571E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	5.570E-06	5.572E-06	5.572E-06	5.572E-06	5.572E-06	0.01
100	5.560E-06	5.561E-06	5.561E-06	5.562E-06	5.561E-06	5.561E-06	5.561E-06	5.561E-06	5.561E-06	5.561E-06	5.561E-06	5.560E-06	5.561E-06	5.561E-06	5.561E-06	5.561E-06	0.01
120	5.550E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	5.549E-06	5.551E-06	5.551E-06	5.551E-06	5.551E-06	0.01
150	5.534E-06	5.535E-06	5.535E-06	5.536E-06	5.535E-06	5.535E-06	5.535E-06	5.535E-06	5.535E-06	5.535E-06	5.535E-06	5.534E-06	5.535E-06	5.535E-06	5.535E-06	5.535E-06	0.01
200	5.508E-06	5.509E-06	5.509E-06	5.510E-06	5.509E-06	5.509E-06	5.509E-06	5.509E-06	5.509E-06	5.509E-06	5.509E-06	5.508E-06	5.509E-06	5.509E-06	5.509E-06	5.509E-06	0.01
300	5.457E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	5.456E-06	5.458E-06	5.458E-06	5.458E-06	5.458E-06	0.01
500	5.355E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	5.355E-06	5.356E-06	5.356E-06	5.356E-06	5.356E-06	0.01
1 000	5.109E-06	5.110E-06	5.110E-06	5.110E-06	5.110E-06	5.110E-06	5.110E-06	5.110E-06	5.111E-06	5.110E-06	5.110E-06	5.109E-06	5.110E-06	5.110E-06	5.110E-06	5.110E-06	0.01
2 000	4.650E-06	4.651E-06	4.651E-06	4.652E-06	4.651E-06	4.651E-06	4.651E-06	4.651E-06	4.653E-06	4.652E-06	4.651E-06	4.650E-06	4.651E-06	4.651E-06	4.651E-06	4.651E-06	0.02
5 000	3.507E-06	3.508E-06	3.508E-06	3.508E-06	3.508E-06	3.507E-06	3.507E-06	3.507E-06	3.510E-06	3.509E-06	3.508E-06	3.507E-06	3.508E-06	3.508E-06	3.508E-06	3.508E-06	0.03
8 000	2.645E-06	2.645E-06	2.645E-06	2.646E-06	2.646E-06	2.644E-06	2.644E-06	2.644E-06	2.648E-06	2.647E-06	2.645E-06	2.645E-06	2.645E-06	2.645E-06	2.645E-06	2.645E-06	0.04
10 000	2.191E-06	2.192E-06	2.192E-06	2.192E-06	2.192E-06	2.190E-06	2.190E-06	2.190E-06	2.195E-06	2.194E-06	2.192E-06	2.191E-06	2.192E-06	2.192E-06	2.192E-06	2.192E-06	0.06
15 000	1.369E-06	1.369E-06	1.370E-06	1.370E-06	1.370E-06	1.368E-06	1.368E-06	1.368E-06	1.373E-06	1.371E-06	1.370E-06	1.369E-06	1.370E-06	1.370E-06	1.370E-06	1.370E-06	0.08
20 000	8.556E-07	8.556E-07	8.557E-07	8.558E-07	8.559E-07	8.545E-07	8.547E-07	8.547E-07	8.581E-07	8.570E-07	8.558E-07	8.555E-07	8.558E-07	8.557E-07	8.557E-07	8.557E-07	0.11
25 000	5.346E-07	5.346E-07	5.347E-07	5.348E-07	5.348E-07	5.338E-07	5.339E-07	5.339E-07	5.366E-07	5.357E-07	5.347E-07	5.346E-07	5.347E-07	5.347E-07	5.347E-07	5.347E-07	0.13
30 000	3.341E-07	3.340E-07	3.341E-07	3.341E-07	3.342E-07	3.334E-07	3.335E-07	3.335E-07	3.355E-07	3.349E-07	3.341E-07	3.340E-07	3.341E-07	3.341E-07	3.341E-07	3.341E-07	0.16
40 000	1.304E-07	1.304E-07	1.304E-07	1.305E-07	1.305E-07	1.301E-07	1.301E-07	1.301E-07	1.312E-07	1.308E-07	1.305E-07	1.304E-07	1.305E-07	1.304E-07	1.304E-07	1.305E-07	0.21
45 000	8.150E-08	8.148E-08	8.151E-08	8.152E-08	8.154E-08	8.125E-08	8.128E-08	8.128E-08	8.201E-08	8.179E-08	8.151E-08	8.149E-08	8.151E-08	8.150E-08	8.151E-08	8.151E-08	0.23
50 000	5.093E-08	5.091E-08	5.093E-08	5.094E-08	5.095E-08	5.075E-08	5.077E-08	5.077E-08	5.128E-08	5.112E-08	5.093E-08	5.092E-08	5.093E-08	5.093E-08	5.093E-08	5.093E-08	0.26
100 000	4.621E-10	4.617E-10	4.621E-10	4.622E-10	4.625E-10	4.587E-10	4.591E-10	4.591E-10	4.683E-10	4.656E-10	4.621E-10	4.620E-10	4.621E-10	4.620E-10	4.620E-10	4.621E-10	0.52

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.46. Time-dependent ^{245}Cm atom densities

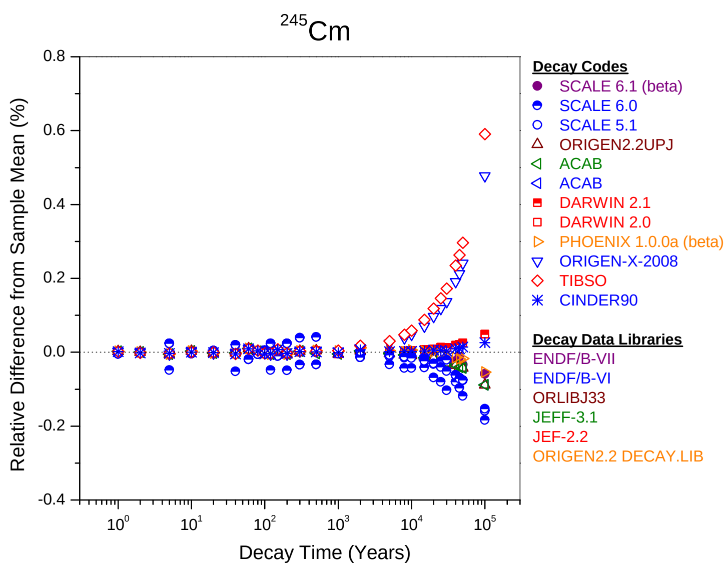
^{245}Cm is an actinide nuclide important for radiological dose assessments. This nuclide has a half-life of $8.5\times10^3 \pm 100$ years and decays by alpha-particle emission and spontaneous fission [20]. The ^{245}Cm half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN 2.2 DECAY.LIB libraries are presented in seconds in Table 92. As seen in the table, the ^{245}Cm half-life values in those libraries are practically identical. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 93. In the table, the calculated ^{245}Cm atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{245}Cm using the evaluated decay codes/data libraries is illustrated in Figure 63. A very small dispersion of the decay calculation results is observed at long decay times (e.g. RSD ≈ 0.25% at 10^5 years).

Table 92. ^{245}Cm half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	2.68239E+11	2.68234E+11	2.68240E+11	2.68234E+11	2.68200E+11
Uncertainty (s)	3.15576E+09	6.31139E+09	6.31152E+09	-	-

Sources: References 12, 13, 20 and 21.

Figure 63. Relative difference from sample mean as a function of decay time for ^{245}Cm atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 93. Decay calculation results for ^{245}Cm (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	0.00
1	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	0.00
2	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	0.00
5	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	1.394E-07	1.395E-07	1.395E-07	1.395E-07	1.395E-07	0.02
10	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	1.394E-07	0.00
20	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	1.393E-07	0.00
40	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	1.390E-07	1.391E-07	1.391E-07	1.391E-07	1.391E-07	0.02
60	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	1.388E-07	0.01
80	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	1.386E-07	0.00
100	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	1.384E-07	0.00
120	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	1.381E-07	1.382E-07	1.382E-07	1.382E-07	1.382E-07	0.02
150	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	1.378E-07	0.01
200	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	1.372E-07	1.373E-07	1.373E-07	1.373E-07	1.373E-07	0.02
300	1.362E-07	1.361E-07	1.361E-07	1.362E-07	1.362E-07	1.362E-07	1.362E-07	1.362E-07	1.362E-07	1.362E-07	1.361E-07	1.361E-07	1.361E-07	1.362E-07	1.361E-07	1.361E-07	0.02
500	1.340E-07	1.339E-07	1.339E-07	1.340E-07	1.339E-07	1.339E-07	1.340E-07	1.340E-07	1.340E-07	1.340E-07	1.339E-07	1.339E-07	1.339E-07	1.339E-07	1.339E-07	1.339E-07	0.02
1 000	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	1.286E-07	0.00
2 000	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	1.185E-07	0.01
5 000	9.280E-08	9.280E-08	9.280E-08	9.280E-08	9.280E-08	9.280E-08	9.280E-08	9.280E-08	9.280E-08	9.282E-08	9.279E-08	9.277E-08	9.279E-08	9.283E-08	9.280E-08	9.280E-08	0.01
8 000	7.266E-08	7.266E-08	7.266E-08	7.266E-08	7.266E-08	7.266E-08	7.266E-08	7.266E-08	7.266E-08	7.269E-08	7.265E-08	7.263E-08	7.265E-08	7.270E-08	7.266E-08	7.266E-08	0.02
10 000	6.172E-08	6.172E-08	6.172E-08	6.172E-08	6.172E-08	6.172E-08	6.173E-08	6.173E-08	6.173E-08	6.176E-08	6.172E-08	6.170E-08	6.172E-08	6.176E-08	6.173E-08	6.173E-08	0.03
15 000	4.105E-08	4.105E-08	4.105E-08	4.105E-08	4.105E-08	4.105E-08	4.106E-08	4.106E-08	4.106E-08	4.109E-08	4.105E-08	4.104E-08	4.105E-08	4.109E-08	4.106E-08	4.106E-08	0.04
20 000	2.730E-08	2.731E-08	2.730E-08	2.730E-08	2.730E-08	2.730E-08	2.731E-08	2.731E-08	2.731E-08	2.734E-08	2.730E-08	2.729E-08	2.730E-08	2.734E-08	2.731E-08	2.731E-08	0.05
25 000	1.816E-08	1.816E-08	1.816E-08	1.816E-08	1.816E-08	1.816E-08	1.817E-08	1.817E-08	1.816E-08	1.819E-08	1.816E-08	1.815E-08	1.816E-08	1.819E-08	1.817E-08	1.816E-08	0.06
30 000	1.208E-08	1.208E-08	1.208E-08	1.208E-08	1.208E-08	1.208E-08	1.208E-08	1.208E-08	1.208E-08	1.210E-08	1.208E-08	1.207E-08	1.208E-08	1.210E-08	1.208E-08	1.208E-08	0.07
40 000	5.342E-09	5.344E-09	5.343E-09	5.342E-09	5.343E-09	5.343E-09	5.346E-09	5.346E-09	5.345E-09	5.356E-09	5.342E-09	5.341E-09	5.342E-09	5.358E-09	5.346E-09	5.345E-09	0.10
45 000	3.553E-09	3.555E-09	3.554E-09	3.553E-09	3.554E-09	3.554E-09	3.556E-09	3.556E-09	3.555E-09	3.563E-09	3.553E-09	3.552E-09	3.553E-09	3.565E-09	3.556E-09	3.555E-09	0.11
50 000	2.363E-09	2.364E-09	2.364E-09	2.363E-09	2.364E-09	2.364E-09	2.365E-09	2.365E-09	2.364E-09	2.371E-09	2.363E-09	2.362E-09	2.363E-09	2.372E-09	2.365E-09	2.365E-09	0.12
100 000	4.002E-11	4.006E-11	4.005E-11	4.002E-11	4.005E-11	4.005E-11	4.010E-11	4.010E-11	4.006E-11	4.028E-11	4.002E-11	4.001E-11	4.002E-11	4.032E-11	4.009E-11	4.008E-11	0.24

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

3.47. Time-dependent ^{246}Cm atom densities

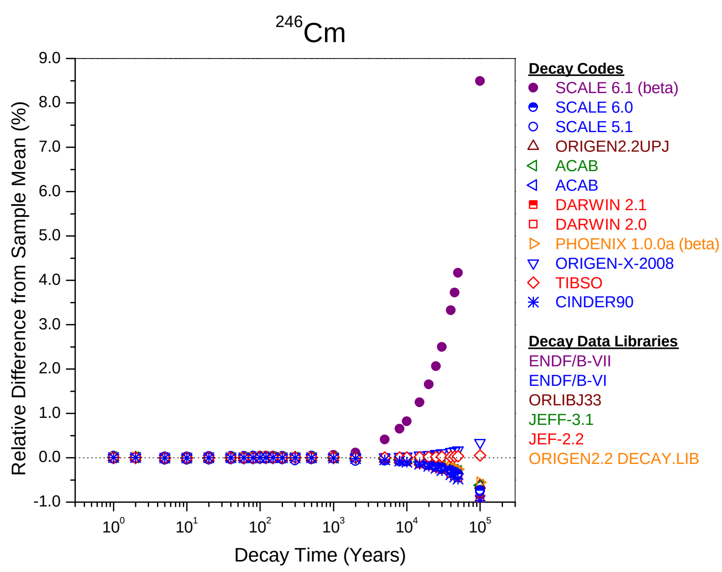
^{246}Cm is an actinide nuclide important for radiological dose assessments. This nuclide has a half-life of $4.76 \times 10^3 \pm 40$ years and decays by alpha-particle emission and spontaneous fission [20]. The ^{246}Cm half-life values and the uncertainties associated with the half-life values in the ENDF/B-VII.0, ENDF/B-VI.8, JEFF-3.1, JEF-2.2, and ORIGEN2.2 DECAY.LIB libraries are presented in seconds in Table 94. The results of the decay calculations using the evaluated decay codes/data libraries are tabulated in Table 95. In the table, the calculated ^{246}Cm atom density values and their sample mean and relative standard deviation values are presented at the decay times specified by the benchmark. A comparison of the results of the decay calculations for ^{246}Cm using the evaluated decay codes/data libraries is illustrated in Figure 64. SCALE 6.1 (beta) predicts higher ^{246}Cm concentrations than the other evaluated decay codes/libraries at long decay times (e.g. ~ 8.5% higher at 10^5 years), as seen in the figure. The observed differences in the calculated ^{246}Cm atom density values are consistent with the differences in the ^{246}Cm half-life values used.

Table 94. ^{246}Cm half-life and associated uncertainty values

Library	ENDF/B-VII.0	ENDF/B-VI.8	JEFF-3.1	JEF-2.2	ORIGEN2.2 DECAY.LIB
Half-life (s)	1.50214E+11	1.49264E+11	1.49267E+11	1.49264E+11	1.49300E+11
Uncertainty (s)	1.26230E+09	3.15569E+09	4.73364E+09	-	-

Sources: References 12, 13, 20 and 21.

Figure 64. Relative difference from sample mean as a function of decay time for ^{246}Cm atom density



Note: Primary decay data source is indicated in the figure for a decay code using multiple sources of decay data.

Table 95. Decay calculation results for ^{246}Cm (atom/barn·cm)

Decay time (years)	Slovak Republic SCALE 5.1	United States SCALE 6.1 beta	Japan ORIGEN 2.2-UPJ	Sweden SCALE 6.0	Spain ACAB 2008[a]	Spain ACAB 2008[b]	France DARWIN 2.1	France DARWIN 2.0	France PHOENIX 1.0.0a beta	Germany ORIGEN-X-2008	Czech Republic SCALE 6.0	Finland SCALE 6.0	Hungary SCALE 6.0	Hungary TIBSO	United States CINDER90	Sample mean	RSD (%)
0	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	1.390E-08	0.00
1	1.389E-08	1.389E-08	1.389E-08	1.390E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	0.02
2	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	0.01
5	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	1.388E-08	1.389E-08	1.389E-08	1.389E-08	1.389E-08	0.02
10	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	1.387E-08	1.388E-08	1.388E-08	1.388E-08	1.388E-08	0.02
20	1.385E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	1.385E-08	1.386E-08	1.386E-08	1.386E-08	1.386E-08	0.02
40	1.381E-08	1.382E-08	1.381E-08	1.382E-08	1.382E-08	1.382E-08	1.382E-08	1.382E-08	1.382E-08	1.382E-08	1.381E-08	1.381E-08	1.381E-08	1.381E-08	1.381E-08	1.381E-08	0.02
60	1.377E-08	1.378E-08	1.377E-08	1.378E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	1.377E-08	0.02
80	1.373E-08	1.374E-08	1.373E-08	1.374E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	1.373E-08	0.02
100	1.369E-08	1.370E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	1.369E-08	0.02
120	1.365E-08	1.366E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	1.365E-08	0.02
150	1.359E-08	1.360E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	1.359E-08	0.02
200	1.349E-08	1.350E-08	1.349E-08	1.350E-08	1.350E-08	1.350E-08	1.350E-08	1.350E-08	1.350E-08	1.350E-08	1.349E-08	1.349E-08	1.349E-08	1.349E-08	1.349E-08	1.349E-08	0.02
300	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	1.329E-08	1.330E-08	1.330E-08	1.330E-08	1.330E-08	0.02
500	1.291E-08	1.292E-08	1.291E-08	1.292E-08	1.291E-08	1.291E-08	1.291E-08	1.291E-08	1.292E-08	1.292E-08	1.291E-08	1.291E-08	1.291E-08	1.291E-08	1.291E-08	1.291E-08	0.02
1 000	1.200E-08	1.201E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	1.200E-08	0.02
2 000	1.037E-08	1.038E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	1.036E-08	1.037E-08	1.037E-08	1.037E-08	1.037E-08	0.04
5 000	6.679E-09	6.709E-09	6.680E-09	6.680E-09	6.680E-09	6.680E-09	6.679E-09	6.679E-09	6.680E-09	6.683E-09	6.679E-09	6.677E-09	6.679E-09	6.682E-09	6.678E-09	6.681E-09	0.12
8 000	4.303E-09	4.334E-09	4.304E-09	4.304E-09	4.304E-09	4.304E-09	4.303E-09	4.303E-09	4.305E-09	4.307E-09	4.303E-09	4.302E-09	4.303E-09	4.306E-09	4.303E-09	4.306E-09	0.19
10 000	3.210E-09	3.239E-09	3.211E-09	3.211E-09	3.211E-09	3.211E-09	3.210E-09	3.210E-09	3.212E-09	3.214E-09	3.210E-09	3.210E-09	3.210E-09	3.213E-09	3.210E-09	3.213E-09	0.24
15 000	1.543E-09	1.564E-09	1.543E-09	1.543E-09	1.543E-09	1.543E-09	1.543E-09	1.543E-09	1.544E-09	1.546E-09	1.543E-09	1.543E-09	1.543E-09	1.545E-09	1.543E-09	1.545E-09	0.36
20 000	7.416E-10	7.550E-10	7.418E-10	7.417E-10	7.419E-10	7.419E-10	7.414E-10	7.414E-10	7.421E-10	7.433E-10	7.417E-10	7.415E-10	7.417E-10	7.428E-10	7.413E-10	7.427E-10	0.48
25 000	3.565E-10	3.645E-10	3.566E-10	3.565E-10	3.566E-10	3.566E-10	3.563E-10	3.563E-10	3.567E-10	3.575E-10	3.565E-10	3.564E-10	3.565E-10	3.572E-10	3.563E-10	3.571E-10	0.60
30 000	1.713E-10	1.760E-10	1.714E-10	1.714E-10	1.714E-10	1.714E-10	1.713E-10	1.713E-10	1.715E-10	1.719E-10	1.713E-10	1.713E-10	1.713E-10	1.718E-10	1.712E-10	1.717E-10	0.72
40 000	3.958E-11	4.102E-11	3.960E-11	3.959E-11	3.960E-11	3.960E-11	3.956E-11	3.956E-11	3.962E-11	3.976E-11	3.959E-11	3.958E-11	3.959E-11	3.971E-11	3.955E-11	3.970E-11	0.96
45 000	1.903E-11	1.980E-11	1.904E-11	1.903E-11	1.904E-11	1.904E-11	1.901E-11	1.901E-11	1.905E-11	1.912E-11	1.903E-11	1.902E-11	1.903E-11	1.909E-11	1.901E-11	1.909E-11	1.07
50 000	9.145E-12	9.561E-12	9.151E-12	9.146E-12	9.151E-12	9.151E-12	9.137E-12	9.137E-12	9.155E-12	9.195E-12	9.145E-12	9.143E-12	9.145E-12	9.181E-12	9.134E-12	9.178E-12	1.20
100 000	6.018E-15	6.578E-15	6.026E-15	6.019E-15	6.026E-15	6.026E-15	6.008E-15	6.008E-15	6.030E-15	6.084E-15	6.019E-15	6.017E-15	6.019E-15	6.066E-15	6.004E-15	6.063E-15	2.45

[a] ENDF/B-VI decay data.

[b] JEFF-3.1 decay data.

4. Criticality calculation results and their analysis

Two different sets of nuclides important to burn-up credit criticality safety analyses consisting of either major actinide nuclides or actinide and fission product nuclides, which are identified in Table 96 as Set 1 and Set 2, respectively, were specified for use in criticality calculations [1].

Table 96. Nuclide sets for criticality calculations

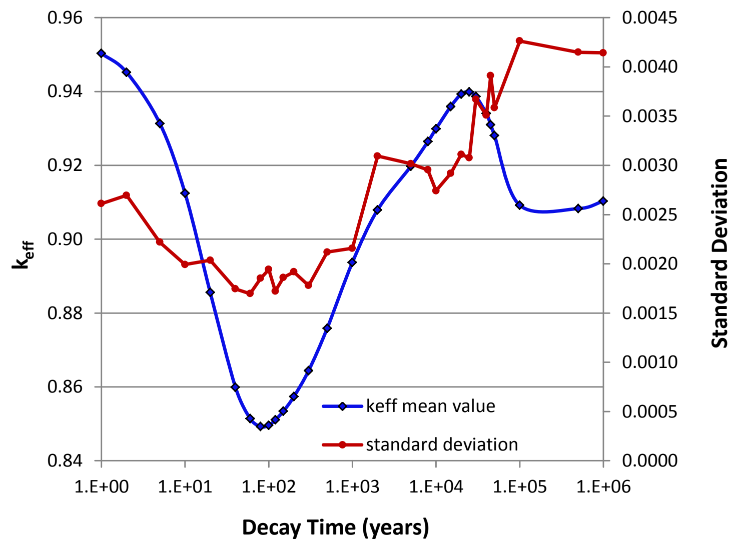
Set 1: Actinide-only burn-up-credit nuclides (11 total)
^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am
Set 2: Actinide + fission product burn-up-credit nuclides (30 total)
^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{143}Nd, ^{145}Nd, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{151}Eu, ^{153}Eu, and ^{155}Gd

The mean and standard deviation values of the participants' k_{eff} results for a representative spent fuel cask are expressed as a function of decay time in Figure 65(a) and (b) for actinide-only fuel compositions and for actinide and fission product fuel compositions, respectively. The average value and the standard deviation of the k_{eff} results for fresh fuel were 1.1486 and 0.0026, respectively. As seen in the figure, k_{eff} values continuously decrease until approximately 100 years after fuel discharge and then increase, with increasing time reaching a peak value at approximately 2.5×10^5 years after fuel discharge. The decrease in k_{eff} for the first 100 years after fuel discharge is caused primarily by the decay of the fissile nuclide ^{241}Pu ($T_{1/2}$ = 14.29 years) to ^{241}Am (neutron absorber), whereas the increase in fuel reactivity after this time is caused by the decay of neutron absorber nuclides ^{238}Pu ($T_{1/2}$ = 87.7 years), ^{240}Pu ($T_{1/2}$ = 6 561 years), ^{241}Am ($T_{1/2}$ = 432.6 years), and ^{243}Am ($T_{1/2}$ = 7 370 years) [see Figure 1(a)].

The organisations participating in the benchmark Phase VII exercise and the criticality codes and cross-section data libraries used by the participants were presented in Table 1. A detailed description of the participants' methods, data, and assumptions is included in Appendix B. The participants' k_{eff} results for the spent fuel cask model using the burn-up-credit actinide compositions are tabulated in Table 97. A comparison of the k_{eff} results to their sample mean for the burn-up-credit actinide compositions is illustrated as a function of decay time in Figure 66. The participants' k_{eff} results for the representative spent fuel cask model using burn-up-credit actinide and fission product compositions are tabulated in Table 98. A comparison of the k_{eff} results to their sample mean for the actinide and fission product compositions is illustrated as a function of decay time in Figure 67. A cross-section data sensitivity and uncertainty analysis of the k_{eff} results performed by the authors of this report for time-dependent fuel compositions consisting of actinide and fission product nuclides important to burn-up credit is described in Section 4.1.

Figure 65. k_{eff} mean and standard deviation values as a function of decay time for fuel compositions consisting of burn-up-credit (a) actinide-only nuclides and (b) actinide and fission product nuclides

(a)



(b)

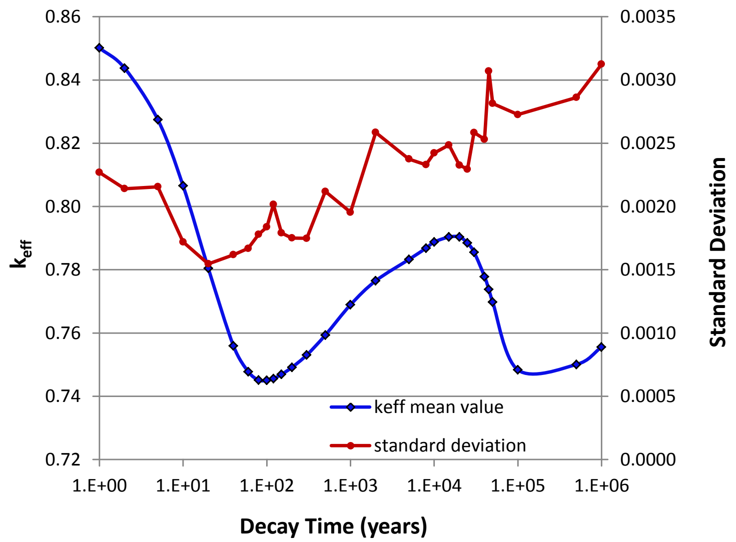


Table 97. Criticality calculation results for actinide-only fuel compositions

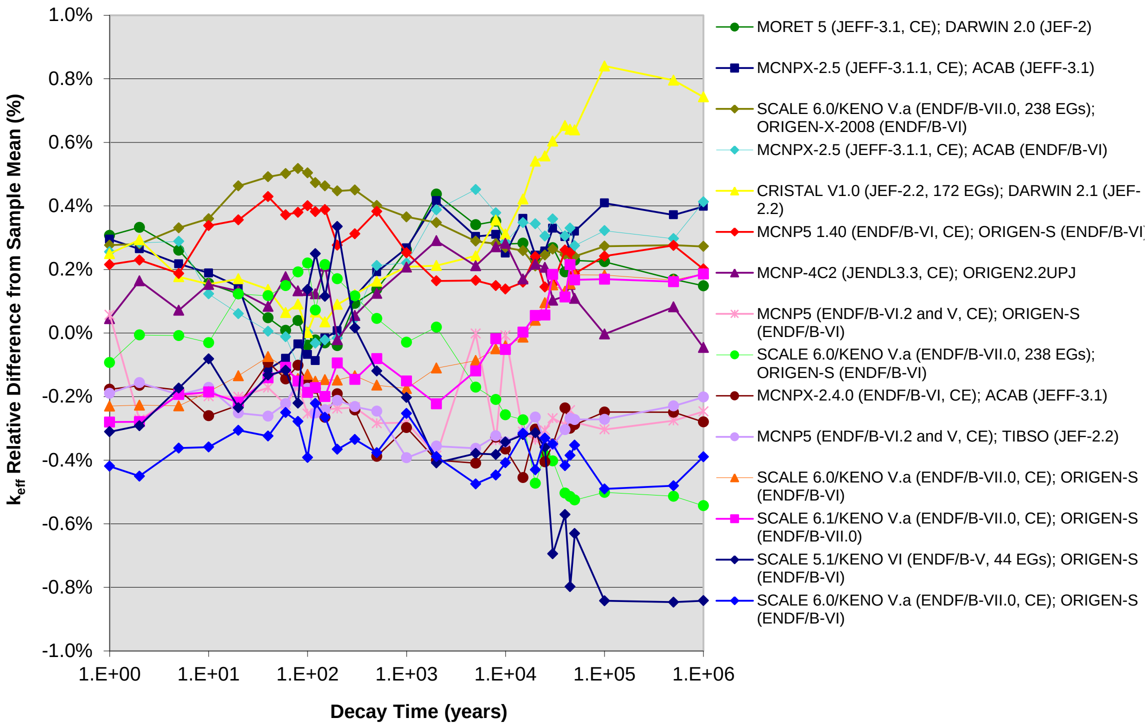
Criticality code	SCALE 5.1/KENO VI		SCALE 6.1/KENO V.a (beta)		MCNP-4C2		SCALE 6.0/KENO V.a		MCNPX-2.5		MCNPX-2.4.0		MCNPX-2.5		CRISTAL V1.0	
Cross-section data	ENDF/B-V, 44 grps		ENDF/B-VII.0, continuous energy		JENDL3.3, continuous energy		ENDF/B-VII.0, continuous energy		JEFF-3.1.1, continuous energy		ENDF/B-VI, continuous energy		JEFF-3.1.1, continuous energy		JEF-2.2, 172 grps	
Decay code	SCALE 5.1/ORIGEN-S		SCALE 6.1/ORIGEN-S (beta)		ORIGEN 2.2-UPJ		SCALE 6.0/ORIGEN-S		ACAB-2008[a]		ACAB-2008[a]		ACAB-2008[b]		DARWIN 2.1	
Decay time (y)	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ
Fresh fuel	1.1429	0.0008	1.1484	0.0003	1.1479	0.0005	1.1485	0.0003	1.1506	0.0004	1.1463	0.0005	1.1506	0.0004	1.1540	0.0003
0	0.9539	0.0008	0.9522	0.0003	0.9562	0.0005	0.9526	0.0003	0.9582	0.0003	0.9523	0.0005	0.9582	0.0003	0.9565	0.0003
1	0.9475	0.0008	0.9478	0.0003	0.9509	0.0005	0.9483	0.0003	0.9533	0.0003	0.9488	0.0005	0.9529	0.0003	0.9529	0.0003
2	0.9426	0.0006	0.9427	0.0003	0.9469	0.0005	0.9432	0.0003	0.9479	0.0003	0.9438	0.0005	0.9480	0.0003	0.9481	0.0003
5	0.9299	0.0008	0.9297	0.0003	0.9321	0.0005	0.9293	0.0003	0.9335	0.0003	0.9298	0.0005	0.9342	0.0003	0.9331	0.0003
10	0.9119	0.0008	0.9110	0.0003	0.9141	0.0005	0.9110	0.0002	0.9144	0.0003	0.9103	0.0005	0.9138	0.0003	0.9141	0.0003
20	0.8837	0.0007	0.8839	0.0003	0.8870	0.0004	0.8846	0.0003	0.8871	0.0003	0.8838	0.0005	0.8864	0.0003	0.8873	0.0003
40	0.8591	0.0006	0.8590	0.0003	0.8609	0.0005	0.8596	0.0003	0.8592	0.0003	0.8594	0.0005	0.8602	0.0003	0.8614	0.0003
60	0.8506	0.0009	0.8507	0.0003	0.8531	0.0004	0.8507	0.0003	0.8510	0.0003	0.8504	0.0005	0.8515	0.0003	0.8522	0.0003
80	0.8476	0.0010	0.8482	0.0003	0.8506	0.0004	0.8483	0.0003	0.8492	0.0003	0.8486	0.0005	0.8486	0.0003	0.8502	0.0003
100	0.8510	0.0007	0.8482	0.0003	0.8510	0.0005	0.8487	0.0003	0.8493	0.0003	0.8485	0.0005	0.8499	0.0003	0.8498	0.0003
120	0.8534	0.0007	0.8498	0.0003	0.8523	0.0005	0.8500	0.0003	0.8505	0.0003	0.8498	0.0005	0.8510	0.0003	0.8518	0.0003
150	0.8547	0.0006	0.8520	0.0003	0.8555	0.0004	0.8524	0.0003	0.8535	0.0003	0.8514	0.0005	0.8535	0.0003	0.8540	0.0003
200	0.8604	0.0006	0.8567	0.0003	0.8574	0.0004	0.8563	0.0002	0.8576	0.0003	0.8559	0.0005	0.8574	0.0003	0.8583	0.0003
300	0.8647	0.0007	0.8633	0.0003	0.8651	0.0005	0.8634	0.0003	0.8656	0.0003	0.8625	0.0005	0.8650	0.0003	0.8656	0.0003
500	0.8751	0.0006	0.8754	0.0003	0.8772	0.0004	0.8747	0.0003	0.8778	0.0003	0.8727	0.0005	0.8780	0.0003	0.8775	0.0003
1 000	0.8921	0.0008	0.8925	0.0003	0.8957	0.0005	0.8923	0.0002	0.8963	0.0003	0.8912	0.0005	0.8958	0.0003	0.8957	0.0003
2 000	0.9043	0.0007	0.9060	0.0003	0.9107	0.0004	0.9070	0.0003	0.9118	0.0003	0.9044	0.0005	0.9116	0.0003	0.9100	0.0003
5 000	0.9164	0.0006	0.9188	0.0003	0.9218	0.0005	0.9191	0.0003	0.9227	0.0003	0.9161	0.0005	0.9240	0.0003	0.9221	0.0003
8 000	0.9230	0.0008	0.9264	0.0003	0.9291	0.0005	0.9261	0.0002	0.9294	0.0003	0.9235	0.0005	0.9300	0.0003	0.9298	0.0003
10 000	0.9268	0.0007	0.9295	0.0003	0.9326	0.0005	0.9296	0.0002	0.9323	0.0003	0.9266	0.0005	0.9327	0.0003	0.9329	0.0003
15 000	0.9331	0.0006	0.9361	0.0003	0.9377	0.0005	0.9359	0.0003	0.9394	0.0003	0.9318	0.0005	0.9393	0.0003	0.9400	0.0003
20 000	0.9365	0.0006	0.9400	0.0003	0.9415	0.0004	0.9398	0.0003	0.9417	0.0003	0.9366	0.0005	0.9427	0.0003	0.9445	0.0003
25 000	0.9366	0.0007	0.9405	0.0003	0.9420	0.0005	0.9409	0.0002	0.9424	0.0003	0.9362	0.0005	0.9429	0.0003	0.9452	0.0003
30 000	0.9323	0.0007	0.9405	0.0003	0.9398	0.0004	0.9402	0.0003	0.9419	0.0003	0.9355	0.0005	0.9422	0.0003	0.9445	0.0003
40 000	0.9289	0.0008	0.9353	0.0003	0.9353	0.0005	0.9354	0.0003	0.9370	0.0003	0.9320	0.0005	0.9371	0.0003	0.9403	0.0003
45 000	0.9238	0.0007	0.9332	0.0003	0.9326	0.0004	0.9326	0.0003	0.9336	0.0003	0.9284	0.0005	0.9343	0.0003	0.9372	0.0003
50 000	0.9223	0.0007	0.9297	0.0003	0.9292	0.0004	0.9299	0.0003	0.9312	0.0003	0.9255	0.0005	0.9307	0.0003	0.9341	0.0003
100 000	0.9017	0.0009	0.9109	0.0003	0.9093	0.0004	0.9110	0.0003	0.9131	0.0003	0.9071	0.0005	0.9123	0.0003	0.9170	0.0003
500 000	0.9008	0.0009	0.9099	0.0003	0.9092	0.0004	0.9100	0.0002	0.9118	0.0003	0.9062	0.0005	0.9112	0.0003	0.9157	0.0003
1 000 000	0.9028	0.0006	0.9121	0.0003	0.9100	0.0004	0.9122	0.0003	0.9141	0.0003	0.9079	0.0005	0.9142	0.0003	0.9172	0.0003

[a] JEFF-3.1 decay data. [b] ENDF/B-VI decay data.

Table 97. Criticality calculation results for actinide-only fuel compositions *(continued)*

Criticality code	MORET5		SCALE 6.0/KENO V.a		SCALE 6/KENO V.a		SCALE 6.0/KENO V.a		MCNP5 1.40		MCNP5		MCNP5			
Cross-section data	JEFF-3.1, continuous energy		ENDF/B-VII.0, 238 grps		ENDF/B-VII.0, 238 grps		ENDF/B-VII.0, continuous energy		ENDF/B-VII, continuous energy		ENDF/B-VI.2 & V, continuous energy		ENDF/B-VI.2 & V, continuous energy			
Decay code	DARWIN 2.0		ORIGEN-X-2008		SCALE 6/ORIGEN-S		SCALE 6.0/ORIGEN-S		SCALE 6.0/ORIGEN-S		TIBSO		SCALE 6.0/ORIGEN-S			
Decay time (y)	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**Sample mean**	**RSD (%)**
Fresh fuel	1.1490	0.0003	1.1493	0.0000	1.1472	0.0004	1.1481	0.0004	1.1487	0.0004	-	-	-	-	1.1485	0.23
0	0.9579	0.0003	0.9574	0.0000	0.9546	0.0003	0.9507	0.0004	0.9571	0.0004	0.9531	0.0002	0.9531	0.0002	0.9548	0.28
1	0.9534	0.0003	0.9531	0.0000	0.9496	0.0003	0.9465	0.0004	0.9525	0.0004	0.9510	0.0003	0.9487	0.0003	0.9503	0.27
2	0.9485	0.0003	0.9480	0.0001	0.9453	0.0003	0.9411	0.0005	0.9475	0.0004	0.9428	0.0002	0.9439	0.0003	0.9452	0.29
5	0.9339	0.0003	0.9346	0.0000	0.9314	0.0004	0.9281	0.0004	0.9332	0.0004	0.9297	0.0002	0.9297	0.0003	0.9313	0.24
10	0.9141	0.0003	0.9160	0.0000	0.9124	0.0003	0.9094	0.0004	0.9158	0.0004	0.9109	0.0002	0.9111	0.0003	0.9124	0.22
20	0.8869	0.0003	0.8899	0.0000	0.8869	0.0004	0.8831	0.0004	0.8890	0.0004	0.8840	0.0002	0.8836	0.0003	0.8856	0.23
40	0.8606	0.0003	0.8644	0.0000	0.8612	0.0003	0.8574	0.0004	0.8639	0.0004	0.8587	0.0002	0.8579	0.0003	0.8599	0.20
60	0.8517	0.0003	0.8559	0.0000	0.8529	0.0003	0.8495	0.0004	0.8548	0.0004	0.8497	0.0002	0.8497	0.0003	0.8514	0.20
80	0.8498	0.0003	0.8539	0.0000	0.8511	0.0004	0.8471	0.0004	0.8527	0.0004	0.8480	0.0002	0.8482	0.0003	0.8492	0.22
100	0.8495	0.0003	0.8541	0.0000	0.8517	0.0003	0.8465	0.0005	0.8532	0.0004	0.8477	0.0002	0.8484	0.0003	0.8496	0.23
120	0.8511	0.0003	0.8553	0.0000	0.8519	0.0003	0.8494	0.0004	0.8545	0.0004	0.8491	0.0002	0.8491	0.0003	0.8511	0.20
150	0.8534	0.0003	0.8576	0.0000	0.8555	0.0003	0.8514	0.0004	0.8570	0.0004	0.8516	0.0002	0.8516	0.0003	0.8535	0.22
200	0.8572	0.0003	0.8614	0.0000	0.8590	0.0003	0.8544	0.0004	0.8599	0.0004	0.8555	0.0002	0.8557	0.0003	0.8573	0.22
300	0.8654	0.0003	0.8685	0.0000	0.8656	0.0003	0.8617	0.0004	0.8673	0.0004	0.8626	0.0002	0.8626	0.0003	0.8644	0.21
500	0.8773	0.0003	0.8796	0.0000	0.8765	0.0003	0.8728	0.0004	0.8795	0.0004	0.8736	0.0002	0.8739	0.0003	0.8759	0.24
1 000	0.8962	0.0003	0.8971	0.0000	0.8936	0.0003	0.8916	0.0005	0.8961	0.0004	0.8913	0.0002	0.8904	0.0003	0.8937	0.24
2 000	0.9120	0.0003	0.9112	0.0001	0.9082	0.0004	0.9045	0.0004	0.9095	0.0004	0.9045	0.0002	0.9048	0.0003	0.9080	0.34
5 000	0.9230	0.0003	0.9225	0.0000	0.9183	0.0003	0.9155	0.0004	0.9214	0.0004	0.9199	0.0004	0.9165	0.0003	0.9198	0.33
8 000	0.9298	0.0003	0.9291	0.0000	0.9246	0.0003	0.9224	0.0004	0.9279	0.0004	0.9234	0.0002	0.9235	0.0003	0.9264	0.32
10 000	0.9326	0.0003	0.9325	0.0000	0.9276	0.0003	0.9262	0.0004	0.9313	0.0004	0.9299	0.0004	0.9268	0.0003	0.9299	0.29
15 000	0.9387	0.0003	0.9385	0.0000	0.9335	0.0004	0.9331	0.0004	0.9376	0.0004	0.9332	0.0002	0.9331	0.0003	0.9360	0.31
20 000	0.9416	0.0003	0.9414	0.0000	0.9350	0.0003	0.9354	0.0004	0.9417	0.0004	0.9363	0.0002	0.9370	0.0003	0.9393	0.33
25 000	0.9424	0.0003	0.9423	0.0000	0.9364	0.0003	0.9369	0.0004	0.9414	0.0004	0.9371	0.0002	0.9368	0.0003	0.9399	0.33
30 000	0.9413	0.0003	0.9413	0.0001	0.9350	0.0004	0.9355	0.0004	0.9402	0.0004	0.9363	0.0002	0.9355	0.0003	0.9387	0.39
40 000	0.9360	0.0003	0.9365	0.0000	0.9295	0.0003	0.9303	0.0004	0.9366	0.0004	0.9315	0.0002	0.9314	0.0003	0.9341	0.38
45 000	0.9336	0.0003	0.9335	0.0000	0.9264	0.0004	0.9276	0.0004	0.9335	0.0004	0.9289	0.0002	0.9287	0.0003	0.9310	0.42
50 000	0.9303	0.0003	0.9304	0.0001	0.9233	0.0003	0.9249	0.0004	0.9299	0.0004	0.9256	0.0002	0.9257	0.0003	0.9281	0.39
100 000	0.9114	0.0003	0.9118	0.0000	0.9048	0.0003	0.9049	0.0004	0.9116	0.0004	0.9066	0.0002	0.9069	0.0003	0.9092	0.47
500 000	0.9100	0.0003	0.9110	0.0000	0.9038	0.0003	0.9041	0.0004	0.9110	0.0003	0.9060	0.0002	0.9064	0.0003	0.9083	0.46
1 000 000	0.9118	0.0003	0.9129	0.0000	0.9055	0.0003	0.9069	0.0004	0.9123	0.0004	0.9082	0.0002	0.9086	0.0003	0.9103	0.46

Figure 66. Comparison of the k_{eff} results to their sample mean for actinide-only fuel compositions



Note: The legend indicates criticality code (nuclear data) and decay code (decay library) used to calculate time-dependent fuel compositions for criticality calculations. EGs = energy groups. CE = continuous energy.

Table 98. Criticality calculation results for actinide and fission product fuel compositions

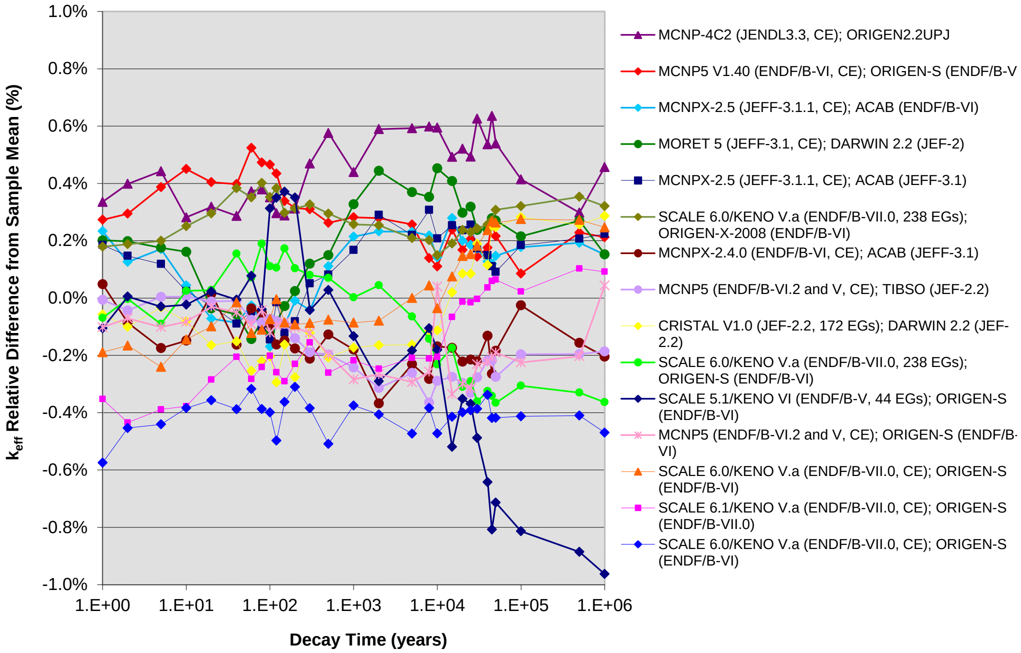
Criticality code	SCALE 5.1/KENO VI		SCALE 6.1/KENO V.a (beta)		MCNP-4C2		SCALE 6.0/KENO V.a		MCNPX-2.5		MCNPX-2.4.0		MCNPX-2.5		CRISTAL V1.0	
Cross-section data	ENDF/B-V, 44 grps		ENDF/B-VII.0, continuous energy		JENDL3.3, continuous energy		ENDF/B-VII.0, continuous energy		JEFF-3.1.1, continuous energy		ENDF/B-VI, continuous energy		JEFF-3.1.1, continuous energy		JEF-2.2, 172 grps	
Decay code	SCALE 5.1/ORIGEN-S		SCALE 6.1/ORIGEN-S (beta)		ORIGEN 2.2-UPJ		SCALE 6.0/ORIGEN-S		ACAB-2008[a]		ACAB-2008[a]		ACAB-2008[b]		DARWIN 2.1	
Decay time (y)	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ	k_{eff}	σ
Fresh fuel	1.1429	0.0008	1.1483	0.0003	1.1479	0.0005	1.1485	0.0003	1.1506	0.0004	1.1463	0.0005	1.1506	0.0004	1.1540	0.0003
0	0.8598	0.0006	0.8590	0.0003	0.8639	0.0005	0.8585	0.0003	0.8627	0.0003	0.8589	0.0005	0.8627	0.0003	0.8601	0.0003
1	0.8494	0.0006	0.8473	0.0003	0.8531	0.0004	0.8487	0.0003	0.8519	0.0003	0.8507	0.0005	0.8523	0.0003	0.8498	0.0003
2	0.8440	0.0009	0.8403	0.0003	0.8473	0.0005	0.8425	0.0003	0.8452	0.0003	0.8432	0.0005	0.8450	0.0003	0.8431	0.0003
5	0.8274	0.0006	0.8244	0.0003	0.8313	0.0005	0.8257	0.0003	0.8286	0.0003	0.8262	0.0005	0.8291	0.0003	0.8274	0.0003
10	0.8066	0.0007	0.8038	0.0003	0.8091	0.0004	0.8056	0.0003	0.8070	0.0003	0.8056	0.0005	0.8072	0.0003	0.8061	0.0003
20	0.7809	0.0007	0.7785	0.0003	0.7832	0.0004	0.7799	0.0003	0.7805	0.0003	0.7808	0.0005	0.7801	0.0003	0.7794	0.0003
40	0.7561	0.0006	0.7546	0.0003	0.7583	0.0004	0.7560	0.0003	0.7555	0.0003	0.7549	0.0004	0.7555	0.0003	0.7550	0.0003
60	0.7487	0.0005	0.7460	0.0003	0.7509	0.0004	0.7472	0.0003	0.7477	0.0003	0.7478	0.0004	0.7479	0.0003	0.7462	0.0003
80	0.7451	0.0006	0.7436	0.0003	0.7482	0.0004	0.7446	0.0002	0.7446	0.0003	0.7450	0.0004	0.7448	0.0003	0.7437	0.0003
100	0.7476	0.0006	0.7438	0.0003	0.7479	0.0004	0.7447	0.0003	0.7442	0.0003	0.7446	0.0004	0.7440	0.0003	0.7438	0.0003
120	0.7484	0.0006	0.7439	0.0003	0.7480	0.0004	0.7458	0.0003	0.7457	0.0003	0.7446	0.0004	0.7452	0.0003	0.7436	0.0003
150	0.7499	0.0005	0.7449	0.0003	0.7493	0.0004	0.7465	0.0003	0.7462	0.0003	0.7460	0.0004	0.7464	0.0003	0.7459	0.0003
200	0.7520	0.0005	0.7476	0.0003	0.7517	0.0004	0.7486	0.0003	0.7487	0.0003	0.7480	0.0004	0.7493	0.0003	0.7473	0.0003
300	0.7529	0.0005	0.7520	0.0003	0.7567	0.0004	0.7525	0.0002	0.7536	0.0003	0.7516	0.0004	0.7529	0.0003	0.7523	0.0003
500	0.7597	0.0005	0.7575	0.0003	0.7638	0.0004	0.7589	0.0002	0.7601	0.0003	0.7585	0.0004	0.7603	0.0003	0.7579	0.0003
1 000	0.7681	0.0006	0.7674	0.0003	0.7725	0.0004	0.7684	0.0003	0.7704	0.0003	0.7677	0.0004	0.7707	0.0003	0.7678	0.0003
2 000	0.7744	0.0006	0.7747	0.0003	0.7812	0.0004	0.7760	0.0003	0.7789	0.0003	0.7738	0.0004	0.7785	0.0003	0.7754	0.0003
5 000	0.7820	0.0009	0.7818	0.0003	0.7881	0.0004	0.7834	0.0003	0.7851	0.0003	0.7816	0.0004	0.7852	0.0003	0.7821	0.0003
8 000	0.7861	0.0007	0.7853	0.0003	0.7916	0.0004	0.7873	0.0003	0.7893	0.0003	0.7847	0.0004	0.7886	0.0003	0.7860	0.0003
10 000	0.7874	0.0007	0.7872	0.0003	0.7935	0.0004	0.7886	0.0003	0.7905	0.0003	0.7875	0.0004	0.7900	0.0003	0.7879	0.0003
15 000	0.7864	0.0006	0.7900	0.0003	0.7944	0.0004	0.7911	0.0003	0.7925	0.0003	0.7891	0.0004	0.7927	0.0003	0.7906	0.0003
20 000	0.7877	0.0006	0.7904	0.0003	0.7946	0.0004	0.7916	0.0003	0.7923	0.0003	0.7887	0.0004	0.7920	0.0003	0.7911	0.0003
25 000	0.7857	0.0006	0.7885	0.0003	0.7925	0.0004	0.7898	0.0002	0.7906	0.0003	0.7869	0.0004	0.7901	0.0003	0.7893	0.0003
30 000	0.7818	0.0006	0.7856	0.0003	0.7906	0.0004	0.7871	0.0003	0.7870	0.0003	0.7839	0.0004	0.7870	0.0003	0.7871	0.0003
40 000	0.7729	0.0008	0.7782	0.0003	0.7821	0.0004	0.7798	0.0003	0.7791	0.0003	0.7769	0.0004	0.7789	0.0003	0.7788	0.0003
45 000	0.7677	0.0006	0.7744	0.0003	0.7789	0.0004	0.7760	0.0003	0.7748	0.0003	0.7719	0.0004	0.7749	0.0003	0.7759	0.0003
50 000	0.7644	0.0008	0.7704	0.0003	0.7741	0.0004	0.7719	0.0003	0.7706	0.0003	0.7685	0.0004	0.7711	0.0003	0.7718	0.0003
100 000	0.7423	0.0006	0.7486	0.0003	0.7515	0.0004	0.7505	0.0003	0.7498	0.0003	0.7482	0.0004	0.7497	0.0003	0.7505	0.0003
500 000	0.7435	0.0006	0.7510	0.0003	0.7524	0.0004	0.7522	0.0003	0.7517	0.0003	0.7490	0.0004	0.7516	0.0003	0.7521	0.0003
1 000 000	0.7484	0.0005	0.7563	0.0003	0.7591	0.0004	0.7575	0.0003	0.7573	0.0003	0.7541	0.0004	0.7568	0.0003	0.7578	0.0003

[a] JEFF-3.1 decay data. [b] ENDF/B-VI decay data.

Table 98. Criticality calculation results for actinide and fission product fuel compositions *(continued)*

Criticality code	MORET5		SCALE 6.0/KENO V.a		SCALE 6.0/KENO V.a		SCALE 6.0/KENO V.a		MCNP5 1.40		MCNP5		MCNP5			
Cross-section data	JEFF-3.1, continuous energy		ENDF/B-VII.0, 238 grps		ENDF/B-VII.0, 238 grps		ENDF/B-VII.0, continuous energy		ENDF/B-VII, continuous energy		ENDF/B-VI.2 & V, continuous energy		ENDF/B-VI.2 & V, continuous energy			
Decay code	DARWIN 2.0		ORIGEN-X-2008		SCALE 6.0/ORIGEN-S		SCALE 6.0/ORIGEN-S		SCALE 6.0/ORIGEN-S		TIBSO		SCALE 6.0/ORIGEN-S			
Decay time (y)	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**k_{eff}**	**σ**	**Sample mean**	**RSD (%)**
Fresh fuel	1.1490	0.0003	1.1493	0.0000	1.1472	0.0004	1.1481	0.0004	1.1487	0.0004	-	-	-	-	1.1485	0.23
0	0.8629	0.0003	0.8619	0.0001	0.8600	0.0003	0.8568	0.0004	0.8634	0.0004	0.8594	0.0002	0.85944	0.0002	0.8604	0.25
1	0.8520	0.0003	0.8518	0.0000	0.8497	0.0003	0.8454	0.0004	0.8526	0.0004	0.8494	0.0002	0.85023	0.0003	0.8500	0.27
2	0.8456	0.0003	0.8455	0.0000	0.8439	0.0003	0.8401	0.0004	0.8464	0.0004	0.8433	0.0002	0.84356	0.0003	0.8438	0.25
5	0.8291	0.0003	0.8293	0.0000	0.8269	0.0003	0.8240	0.0005	0.8309	0.0004	0.8268	0.0002	0.82768	0.0003	0.8274	0.26
10	0.8081	0.0003	0.8088	0.0000	0.8070	0.0003	0.8037	0.0004	0.8104	0.0003	0.8061	0.0002	0.80684	0.0003	0.8066	0.21
20	0.7804	0.0003	0.7830	0.0000	0.7809	0.0003	0.7779	0.0004	0.7838	0.0003	0.7805	0.0002	0.78059	0.0003	0.7805	0.20
40	0.7557	0.0003	0.7590	0.0000	0.7573	0.0003	0.7532	0.0004	0.7591	0.0003	0.7558	0.0002	0.75606	0.0003	0.7559	0.21
60	0.7470	0.0003	0.7507	0.0000	0.7486	0.0003	0.7457	0.0004	0.7520	0.0005	0.7474	0.0002	0.7475	0.0003	0.7478	0.22
80	0.7448	0.0003	0.7484	0.0000	0.7468	0.0003	0.7425	0.0004	0.7489	0.0003	0.7451	0.0002	0.74475	0.0003	0.7451	0.24
100	0.7444	0.0003	0.7479	0.0000	0.7461	0.0003	0.7423	0.0004	0.7487	0.0003	0.7444	0.0002	0.74473	0.0003	0.7450	0.25
120	0.7452	0.0003	0.7487	0.0000	0.7466	0.0003	0.7421	0.0005	0.7491	0.0003	0.7451	0.0002	0.74521	0.0003	0.7456	0.27
150	0.7469	0.0003	0.7493	0.0000	0.7484	0.0003	0.7444	0.0004	0.7496	0.0003	0.7465	0.0002	0.74644	0.0003	0.7470	0.24
200	0.7495	0.0003	0.7517	0.0000	0.7501	0.0003	0.7470	0.0004	0.7517	0.0003	0.7486	0.0002	0.74827	0.0003	0.7492	0.23
300	0.7541	0.0003	0.7557	0.0000	0.7538	0.0003	0.7503	0.0004	0.7555	0.0003	0.7523	0.0002	0.75177	0.0003	0.7530	0.23
500	0.7606	0.0003	0.7617	0.0000	0.7600	0.0003	0.7556	0.0004	0.7615	0.0003	0.7580	0.0002	0.75797	0.0003	0.7593	0.28
1 000	0.7716	0.0003	0.7711	0.0000	0.7691	0.0003	0.7662	0.0004	0.7713	0.0003	0.7669	0.0002	0.76722	0.0003	0.7689	0.25
2 000	0.7801	0.0003	0.7786	0.0000	0.7770	0.0003	0.7735	0.0004	0.7788	0.0003	0.7746	0.0002	0.77422	0.0003	0.7765	0.33
5 000	0.7863	0.0003	0.7850	0.0001	0.7829	0.0003	0.7797	0.0004	0.7854	0.0003	0.7811	0.0002	0.78136	0.0003	0.7832	0.30
8 000	0.7897	0.0003	0.7885	0.0000	0.7858	0.0003	0.7839	0.0004	0.7880	0.0003	0.7849	0.0002	0.78405	0.0003	0.7868	0.30
10 000	0.7924	0.0003	0.7900	0.0000	0.7870	0.0003	0.7851	0.0004	0.7897	0.0003	0.7892	0.0003	0.78655	0.0003	0.7887	0.31
15 000	0.7937	0.0003	0.7920	0.0000	0.7891	0.0003	0.7872	0.0004	0.7924	0.0003	0.7878	0.0002	0.7883	0.0003	0.7903	0.31
20 000	0.7928	0.0003	0.7923	0.0000	0.7880	0.0003	0.7873	0.0004	0.7918	0.0003	0.7881	0.0002	0.78811	0.0003	0.7904	0.29
25 000	0.7911	0.0003	0.7904	0.0000	0.7863	0.0003	0.7855	0.0004	0.7902	0.0003	0.7861	0.0002	0.78598	0.0003	0.7885	0.29
30 000	0.7875	0.0003	0.7875	0.0000	0.7828	0.0003	0.7826	0.0004	0.7868	0.0003	0.7838	0.0002	0.78346	0.0003	0.7856	0.33
40 000	0.7798	0.0003	0.7799	0.0000	0.7754	0.0003	0.7753	0.0004	0.7793	0.0003	0.7762	0.0002	0.77623	0.0003	0.7778	0.33
45 000	0.7761	0.0003	0.7760	0.0000	0.7713	0.0003	0.7707	0.0004	0.7760	0.0003	0.7724	0.0002	0.77226	0.0003	0.7738	0.40
50 000	0.7720	0.0003	0.7723	0.0000	0.7671	0.0003	0.7667	0.0004	0.7716	0.0003	0.7685	0.0002	0.7678	0.0003	0.7699	0.37
100 000	0.7500	0.0003	0.7508	0.0000	0.7461	0.0003	0.7453	0.0004	0.7490	0.0003	0.7467	0.0002	0.74692	0.0003	0.7483	0.36
500 000	0.7522	0.0003	0.7528	0.0000	0.7477	0.0003	0.7471	0.0004	0.7519	0.0003	0.7487	0.0002	0.74871	0.0003	0.7500	0.38
1 000 000	0.7568	0.0003	0.7581	0.0000	0.7529	0.0003	0.7521	0.0004	0.7573	0.0003	0.7560	0.0003	0.75424	0.0003	0.7555	0.41

Figure 67. Comparison of the k_{eff} results to their sample mean for actinide and fission product fuel compositions



Note: The legend indicates criticality code (nuclear data) and decay code (decay library) used to calculate time-dependent fuel compositions for criticality calculations. EGs = energy groups. CE = continuous energy.

4.1. Cross-section sensitivity and uncertainty analysis

The k_{eff} benchmark results varied depending on the decay time, as illustrated by their relative difference from sample mean shown in Figure 66 and Figure 67 for actinide-only and for actinide and fission product fuel compositions, respectively. The largest variability of the calculated k_{eff} values for actinide-only fuel compositions and for actinide and fission product fuel compositions was obtained at 10^5 years (RSD = 0.47%) and at 10^6 years (RSD = 0.41%), respectively. The average value and the standard deviation of the k_{eff} results for fresh fuel were 1.1486 and 0.0025, respectively. A dispersion of the benchmark criticality calculation results may be caused by a dispersion of the calculated nuclide atom density values, different nuclear cross-section data, and modeling and numerical approximations made by the participants.

The impact of the variability of the atom density results on k_{eff} is considered to be negligible based on the results of a previously published sensitivity/uncertainty analysis and on the analysis of the decay calculation results presented in Chapter 3 of this report. A sensitivity/uncertainty analysis provided in [23], has determined that the JEFF-3.1 decay data uncertainty values have a negligible effect on the k_{eff} values for the generic spent fuel cask. The analysis of the decay calculation results presented in Chapter 3 identified a limited number of burn-up credit nuclides with dispersions greater than 1% of the atom density results, including ^{99}Tc, ^{151}Sm, ^{155}Gd, ^{233}U, ^{234}U, ^{237}Np, ^{241}Pu, ^{242}Pu, and ^{241}Am. However, the k_{eff} sensitivities to the total cross sections of those nuclides are negligible based on the cross-section data sensitivity and uncertainty analysis presented further. Therefore, the effect on k_{eff} of the variability in the calculated atom densities of those nuclides is also considered to be negligible.

To evaluate the impact of cross-section data uncertainties on k_{eff}, a sensitivity and uncertainty analysis was performed using the TSUNAMI tools in SCALE [5]. The TSUNAMI calculations used the SCALE 238-group ENDF/B-VII cross-section library and the SCALE 44-group covariance library, which has been developed from a variety of sources including evaluations from ENDF/B-VII, ENDF/B-VI, and JENDL. Energy and region integrated k_{eff} sensitivities to nuclide total and reaction-specific cross sections and the relative uncertainty in k_{eff} due to cross-section covariance data were calculated using

TSUNAMI. The sensitivity of k_{eff} to a particular nuclide-reaction pair macroscopic cross section, referred to as the sensitivity coefficient, provides a measure of the first-order effect of perturbations in the nuclear reaction data for the nuclide on k_{eff}.

The sensitivity coefficients for the actinide and fission product fuel compositions are illustrated as a function of the decay time in Figure 68. As seen in the figure, k_{eff} has large sensitivities to ^{239}Pu, ^{235}U, and ^{238}U total cross sections. Therefore, uncertainties associated with the cross-section data for those nuclides also have a dominating effect on the uncertainty in k_{eff}. The values of the one sigma uncertainty in k_{eff} due to cross-section covariance data, which were obtained directly from TSUNAMI calculations, are represented as a function of decay time in Figure 69 for the actinide and fission product fuel compositions. The value of the relative uncertainty in k_{eff} due to cross-section covariance data varied from 0.48% (10^5 years) to 0.76% (10^2 years). The k_{eff} values and the values of the one sigma uncertainty in k_{eff} due to the dispersion of the calculation results are also shown in Figure 69 for comparison purposes. The relative uncertainty in k_{eff} due to cross-section covariance data is slightly larger than the maximum RSD of the k_{eff} values (0.41%) calculated by the participants. Hence, the small variability of the k_{eff} benchmark calculation results may be predominantly attributed to the criticality calculation methods and cross-section data.

Figure 68. k_{eff} sensitivity to nuclide total cross section as a function of decay time for fuel compositions consisting of burn-up credit actinide and fission product nuclides

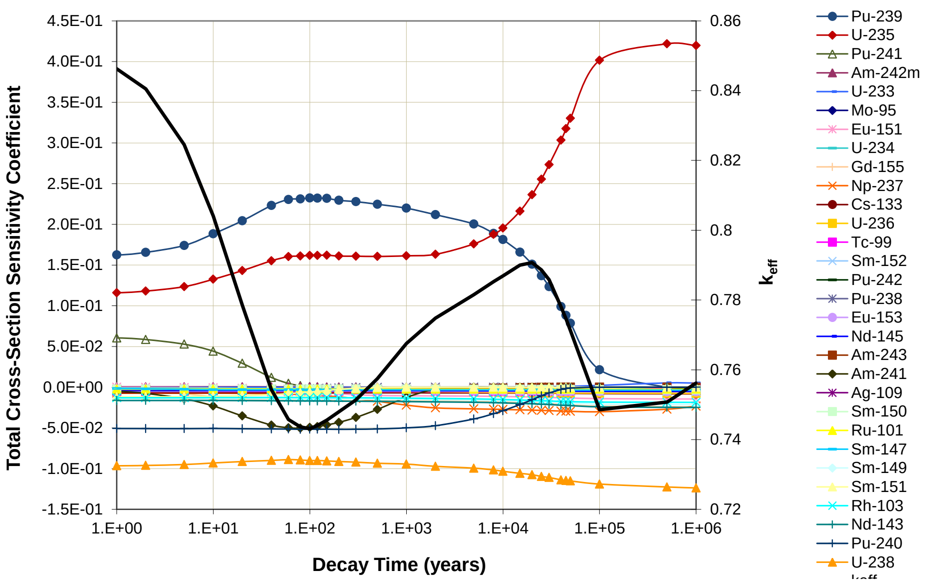
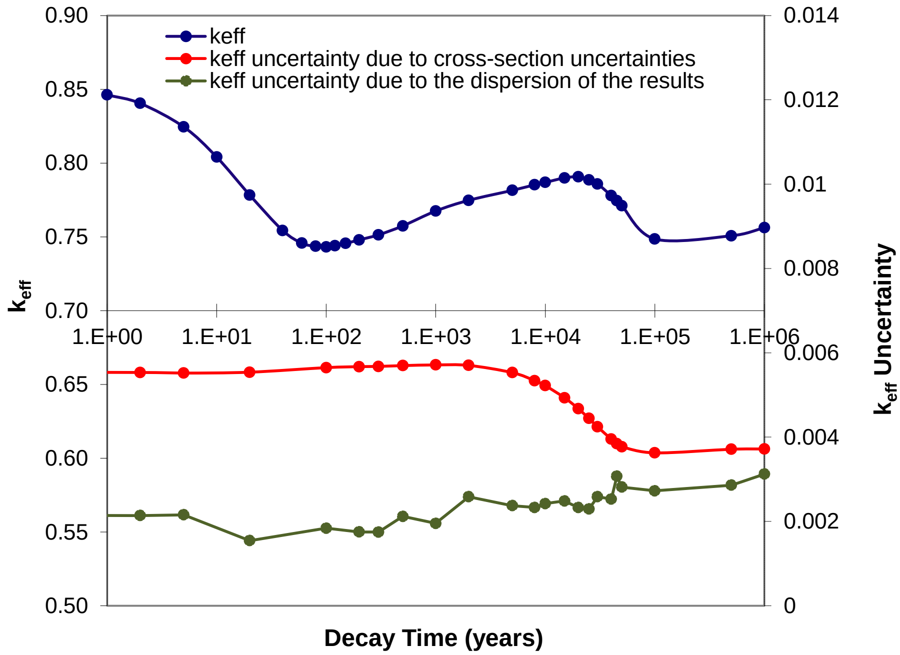


Figure 69. Comparison of the one-sigma uncertainty in k_{eff} due to cross-section uncertainties and the one-sigma uncertainty in k_{eff} due to the dispersion of the calculation results for fuel compositions consisting of burn-up credit actinide and fission product nuclides



Conclusions

Contributions from 15 organisations in 10 countries were submitted to the Phase VII benchmark, the purpose of which was to evaluate the ability of decay codes to predict the concentrations of nuclides important to radiological dose assessments and burn-up credit criticality analyses and the ability of criticality codes to predict k_{eff} values in a generic spent fuel cask over the time duration relevant to long-term storage and disposal of spent nuclear fuel. The results obtained by the participants using a variety of codes and nuclear data were evaluated in this report. Differences observed in the calculated atom densities for nuclides important to burn-up credit criticality analyses and radiological dose assessments may be attributed to (1) different decay data, (2) the ability of the decay codes to consider relevant precursor decay chains contributing to the formation of a nuclide of interest, and (3) approximations related to the number of time steps allowed by the code. The observed variability of the k_{eff} results is bounded by the evaluated uncertainty in k_{eff} due to cross-section covariance data and may be predominantly attributed to the criticality calculation methods and cross-section data.

The dispersion of the decay calculation results varied depending on the nuclide and decay time. For the major burn-up credit actinide nuclides ^{235}U, ^{236}U, ^{238}U, and ^{239}Pu, the decay calculation results were practically identical. The greatest variability of the decay calculation results was obtained for ^{126}Sn, ^{126}Sb, and ^{126m}Sb (e.g. RSD ≈ 150% at 10^6 years). For many nuclides, correlations were established between the half-life and/or branching ratio values associated with the evaluated decay libraries and the observed trends of nuclide concentration values relative to the mean values. A review of the decay data in the ENDF/B-VII.0, JEFF-3.1, ENDF/B-VI.8, JEF-2, ENSDF, and JENDL-3.3 libraries identified a series of nuclides for which significant differences exist among the decay data evaluations. Nuclides most impacted by different half-life values associated with the evaluated libraries were ^{14}C, ^{41}Ca, ^{59}Ni, ^{79}Se, ^{90}Sr, ^{94}Nb, ^{93}Mo, ^{99}Tc, ^{126}Sn, ^{151}Sm, ^{155}Eu, ^{229}Th, ^{232}U, ^{236}Np, ^{236}Pu, and ^{246}Cm. Different branching ratio values for the beta decay transition of ^{93}Zr to ^{93m}Nb affected the calculated ^{93m}Nb densities. Differences observed between the atom densities calculated with PHOENIX 1.0.0a (beta) and the atom densities calculated with the other decay codes for ^{41}Ca, ^{59}Ni, ^{93m}Nb, ^{228}Ra, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{242}Pu, and ^{242m}Am may be attributed to the differences between the earlier ENDF/B-IV decay data in the ORIGEN2.2 decay library and the more recent decay data evaluations. ORIGEN-X-2008 atom densities for nuclides such as ^{226}Ra, ^{229}Th, ^{232}U, ^{233}U, and ^{237}Np show small deviations from the atom density values calculated with the other decay codes due to a limited number of decay steps used by the code that impacted the accuracy with which contributions from short-lived parents were calculated. Differences between the TIBSO atom densities and the other calculated atom densities were observed for a series of nuclides including ^{94}Nb, ^{210}Pb, ^{226}Ra, ^{228}Ra, ^{227}Ac, ^{230}Th, ^{234}U, ^{241}Pu, and ^{241}Am. The ^{210}Pb atom densities calculated with CINDER 90 were significantly lower than the ^{210}Pb atom densities calculated using the other decay codes.

The dispersion of the participants' k_{eff} results varied depending on the decay time. The average value and the RSD of the k_{eff} results for fresh fuel were 1.1486 and 0.22%, respectively. The calculated k_{eff} values for actinide-only fuel compositions had a maximum RSD of 0.47% at 10^5 years; the maximum RSD of the k_{eff} values for actinide and fission product fuel compositions was 0.41% at 10^6 years. The impact of cross-section data uncertainties on k_{eff} was evaluated for fuel compositions containing actinide and fission product nuclides important to burn-up credit. Energy and region integrated k_{eff} sensitivities to nuclide total and reaction-specific cross sections and the relative uncertainty in k_{eff} due to cross-section covariance data were calculated using the TSUNAMI sequence in SCALE. The relative uncertainty in k_{eff} due to cross-section covariance data, which varied from 0.48% (10^5 years) to 0.76% (10^2 years), was slightly larger than the maximum RSD of the k_{eff} values (0.41%) calculated by the participants. Hence, the small variability of the k_{eff} benchmark calculation results may be predominantly attributed to the criticality calculation methods and cross-section data.

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Abbreviations

α	alpha-particle emission
β^-	beta-particle emission
ENDF	United States Evaluated Nuclear Data File
IT	isomeric transition
JEF	Joint European File
JEFF	NEA Joint Evaluated Fission and Fusion File
JENDL	Japan Evaluated Nuclear Data Library
k_{eff}	effective neutron multiplication factor
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
RSD	relative standard deviation
SNF	spent nuclear fuel
$T_{1/2}$	half-life

Appendix A. Specification for the Burn-up Credit Criticality Safety Benchmark Phase VII

UO_2 Fuel: Study of spent fuel compositions for long-term disposal

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November, 2008

1. Introduction

The concept of taking credit for a reduction in reactivity due to fuel burn-up is commonly referred to as *burn-up credit*. The reduction in reactivity that occurs with fuel burn-up is due to the change in concentration (net reduction) of fissile nuclides and the production of actinide and fission-product neutron absorbers. After spent nuclear fuel (SNF) is discharged from a reactor, the reactivity continues to vary as a function of time due to the decay of unstable isotopes.

Burn-up credit analyses for storage and transport consider timeframes that are extremely short (typically less than 100 years), as compared to the timeframe of interest to long-term disposal (e.g. 10 000 years after closure in the United States). This benchmark proposes to study the ability of relevant computer codes and associated nuclear data to predict spent fuel isotopic compositions and corresponding k_{eff} values in a cask configuration over the time duration relevant to SNF disposal. It is recognised that the benefits of this proposed benchmark are largely confined to revealing differences in nuclear data for decay constants (half-lives, branching fractions), which are widely considered to be well-known. However, the results of this exercise may serve to reveal differences in international nuclear data sets and/or improve understanding and confidence in our ability to predict k_{eff} and source terms for timeframes relevant to long-term disposal of SNF.

The benchmark is divided into two sets of calculations:

- Decay calculations for provided PWR UO_2 discharged fuel compositions
- Criticality (k_{eff}) calculations for a representative cask model

Participants are requested to perform decay calculations, using the provided PWR fuel compositions as a starting point, and criticality calculations for the PWR fuel in the OECD cask model for 30 post-irradiation time steps, out to 1 000 000 years. Decay calculations will be performed for nuclides that are relevant to burn-up credit and to public dose from nuclear waste repositories. Although it is acknowledged that the physical condition of the fuel will change over such a long time period, there is interest in the change in isotopic compositions over this duration, as well as interest in the relative behaviour of k_{eff} over this duration. Analysis of the results will involve comparison of participant's isotopic compositions and k_{eff} values as a function of time.

2. Decay calculations

The isotopes that are considered relevant to burn-up-credit criticality calculations and those that are potential contributors to radiation dose to the public from nuclear waste repositories are listed in the "Benchmark nuclide" column in Table A.1. Utilising the discharge fuel composition provided in Table A.1 for a representative PWR assembly of 4.5-wt% ^{235}U initial enrichment and 50-GWd/MTU burn-up, participants are requested to perform decay calculations and report atom densities for the Benchmark nuclides designated in Table A.1 and times listed in Table A.2. The discharge fuel composition provided contains only the benchmark nuclides designated in Table A.1 and their precursors that are relevant to the decay calculations. The nuclide atom densities for the discharge fuel composition, in atom/barn·cm, are provided with four significant digits in Table A.1 and in a text file attached to this benchmark specification.

Table A.1. Discharge fuel composition (4.5 initial wt% ^{235}U, 50-GWd/MTU) for calculating time-dependent spent fuel compositions

Isotope	Atom density (atom/barn·cm)	Benchmark nuclide[a]	Area of applicability		
			Actinide-only burn-up credit	Actinide + FP burn-up credit	Public dose
^{14}C	1.8462E-09	X			X
^{16}O[b]	4.7923E-02		X	X	
^{36}Cl[c]	1.0000E-06	X			X
^{41}Ca[c]	1.0000E-06	X			X
^{59}Ni[c]	1.0000E-06	X			X
^{79}Se	5.0582E-07	X			X
^{93}Zr	6.3637E-05	X			X
^{93}Rb	1.6072E-12				
^{90}Sr	4.8584E-05	X			X
^{93}Sr	2.3719E-10				
^{93}Y	1.9886E-08				
^{95}Y	3.8958E-10				
^{93m}Nb	6.6305E-11	X			X
^{94}Nb	6.2143E-11	X			X
^{95}Nb	1.9348E-06				
^{93}Mo	1.1478E-14	X			X
^{95}Mo	6.0803E-05	X		X	
^{99}Mo	1.7898E-07				
^{101}Mo	6.2291E-10				
^{99m}Tc	1.4716E-08				
^{99}Tc	6.6733E-05	X		X	X
^{101}Tc	6.0649E-10				
^{101}Ru	6.5615E-05	X		X	
^{103}Ru	2.3665E-06				
^{103}Rh	3.4702E-05	X		X	
^{107}Pd	1.8503E-05	X			X
^{109}Pd	8.5605E-09				
^{109}Ag	6.0729E-06	X		X	

[a] Nuclides that are relevant to either burn-up credit or public dose. Benchmark nuclides selected based on a review of the following references and other preliminary European studies.
Ref. 1: J. C. Wagner and C. E. Sanders, *Assessment of Reactivity Margins and Loading Curves for PWR Burnup Credit Cask Analyses*, NUREG/CR-6800 (ORNL/TM-2002/6), US Nuclear Regulatory Commission, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 2003.
Ref. 2: *Radionuclide Screening*, ANL-WIS-MD-000006 REV 02, Sandia National Laboratories, Las Vegas, Nevada (2007).
Ref. 3: *Project Opalinus Clay Safety Report: Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-Level Waste and Long-Lived Intermediate-Level Waste (Entsorgungsnachweis)*, NAGRA Technical Report NTB 02-05, NAGRA, Wettingen, Switzerland (2002).
[b] ^{16}O concentration is provided for criticality calculations only.
[c] The nuclide does not exist in the calculated discharge inventory for the PWR assembly.

Isotope	Atom density (atom/barn·cm)	Benchmark nuclide[a]	Area of applicability		
			Actinide-only burn-up credit	Actinide + FP burn-up credit	Public dose
^{126}Sn	1.2852E-06	X			X
^{126}Sb	2.3835E-10	X			X
^{126m}Sb	3.1762E-13	X			X
^{129}Sb	1.9663E-09				
^{129m}Te	6.4572E-08				
^{129}I	1.0251E-05	X			X
^{133}I	6.1772E-08				
^{135}I	1.8776E-08				
^{133}Xe	3.7597E-07				
^{135}Xe	1.0156E-08				
^{133}Cs	6.9874E-05	X		X	
^{135}Cs	3.4626E-05	X			X
^{137}Cs	7.5114E-05	X			X
^{143}Pr	6.9646E-07				
^{147}Pr	2.1435E-10				
^{149}Pr	2.0197E-11				
^{143}Nd	4.6567E-05	X		X	
^{145}Nd	3.8049E-05	X		X	
^{147}Nd	2.5090E-07				
^{149}Nd	9.9358E-10				
^{147}Pm	7.4886E-06				
^{149}Pm	4.4831E-08				
^{151}Pm	8.6483E-09				
^{147}Sm	4.7086E-06	X		X	
^{149}Sm	1.3806E-07	X		X	
^{150}Sm	1.6254E-05	X		X	
^{151}Sm	9.7106E-07	X		X	X
^{152}Sm	6.3220E-06	X		X	
^{153}Sm	3.8127E-08				
^{155}Sm	2.3852E-11				
^{151}Eu	1.5639E-09	X		X	
^{152}Eu	3.2421E-09				
^{153}Eu	6.6248E-06	X		X	
^{155}Eu	3.4461E-07				
^{155}Gd	5.4622E-09	X		X	
^{210}Pb	3.8862E-18	X			X
^{222}Rn	9.3947E-21				
^{226}Ra	1.4422E-15	X			X
^{228}Ra	9.3958E-22	X			X
^{227}Ac	3.2593E-16	X			X
^{226}Th	1.9447E-22				
^{229}Th	5.9651E-14	X			X
^{230}Th	5.5098E-11	X			X

Isotope	Atom density (atom/barn·cm)	Benchmark nuclide[a]	Area of applicability		
			Actinide-only burn-up credit	Actinide + FP burn-up credit	Public dose
^{232}Th	1.2690E-11	X			X
^{231}Th	4.8649E-14				
^{231}Pa	1.8739E-11	X			X
^{230}U	1.8514E-19				
^{232}U	2.3106E-11	X			X
^{233}U	8.7082E-11	X	X	X	X
^{234}U	4.5729E-06	X	X	X	X
^{235}U	2.4950E-04	X	X	X	X
^{236}U	1.5044E-04	X	X	X	X
^{237}U	2.7902E-07				
^{238}U	2.1947E-02	X	X	X	X
^{239}U	1.2843E-08				
^{240}U	1.3550E-20				
^{235}Np	6.7582E-13				
^{236}Np	1.2422E-11				
^{236m}Np	2.8487E-13				
^{237}Np	1.9889E-05	X		X	X
^{238}Np	4.8303E-08				
^{239}Np	1.8489E-06				
^{240}Np	5.2420E-11				
^{236}Pu	3.5918E-11				
^{237}Pu	2.0813E-11				
^{238}Pu	9.3508E-06	X	X	X	X
^{239}Pu	1.8344E-04	X	X	X	X
^{240}Pu	7.2862E-05	X	X	X	X
^{241}Pu	4.7994E-05	X	X	X	X
^{242}Pu	1.9005E-05	X	X	X	X
^{243}Pu	4.6387E-09				
^{244}Pu	6.7468E-10				
^{245}Pu	3.2226E-14				
^{246}Pu	2.2173E-16				
^{239}Am	1.8587E-16				
^{240}Am	8.0708E-14				
^{241}Am	2.2311E-06	X	X	X	X
^{242}Am	3.8342E-09				
^{242m}Am	5.2630E-08	X		X	X
^{243}Am	5.6091E-06	X		X	X
^{242}Cm	5.9799E-07				
^{243}Cm	2.2037E-08				
^{244}Cm	2.3542E-06				
^{245}Cm	1.3952E-07	X			X
^{246}Cm	1.3896E-08	X			X

Table A.2. Times for calculating and reporting isotopic compositions

Time case number	Time (y)	Time case number	Time (y)
1	0	16	1 000
2	1	17	2 000
3	2	18	5 000
4	5	19	8 000
5	10	20	10 000
6	20	21	15 000
7	40	22	20 000
8	60	23	25 000
9	80	24	30 000
10	100	25	40 000
11	120	26	45 000
12	150	27	50 000
13	200	28	100 000
14	300	29	500 000
15	500	30	1 000 000

3. k_{eff} Calculations

Criticality calculations are to be performed for a representative PWR cask model utilising the PWR spent fuel isotopic compositions from the decay calculations for nuclides relevant to burn-up credit corresponding to the times listed in Table A.2. The cask model to be used is described below and is identical to the cask model used in Phase IID of the Expert Group on Burn-up Credit Benchmarks. k_{eff} values will be calculated for both actinide only and actinide and fission product cases. The actinide only cases should include ^{16}O and the nuclides identified as "Set 1" in Table A.3. The actinide and fission product case should include ^{16}O and the nuclides identified as "Set 2" in Table A.3.

Table A.3. Nuclide sets to be used in k_{eff} calculations

Set 1: Actinide-only burn-up-credit nuclides (11 total)
^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{241}Am
Set 2: Actinide + fission product burn-up-credit nuclides (30 total)
^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{242m}Am, ^{243}Am, ^{95}Mo, ^{99}Tc, ^{101}Ru, ^{103}Rh, ^{109}Ag, ^{133}Cs, ^{143}Nd, ^{145}Nd, ^{147}Sm, ^{149}Sm, ^{150}Sm, ^{151}Sm, ^{152}Sm, ^{151}Eu, ^{153}Eu, and ^{155}Gd

3.1. Geometry data

The representative OECD cask loaded with intact UO_2 17×17 assemblies is the criticality model for k_{eff} calculations. The UO_2 assembly geometry and the locations for 25 guide tubes are illustrated in Figure A.1. Fuel rod and guide tube radial dimensions are shown in Figures A.2 and A.3, respectively. Cross-section views of the cask model for use in criticality calculations are provided in Figures A.4 through A.6.

Figure A.1. UO_2 assembly geometry and guide tube locations

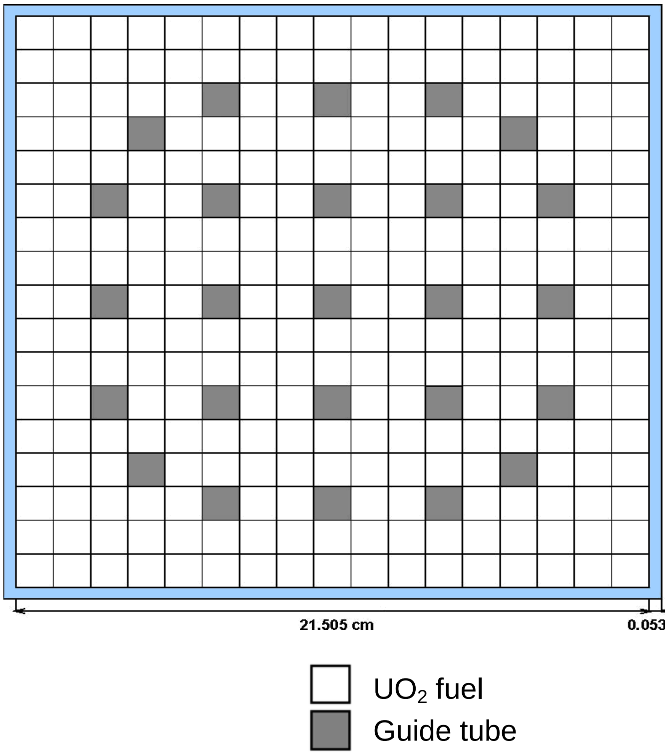


Figure A.2. Fuel rod geometry

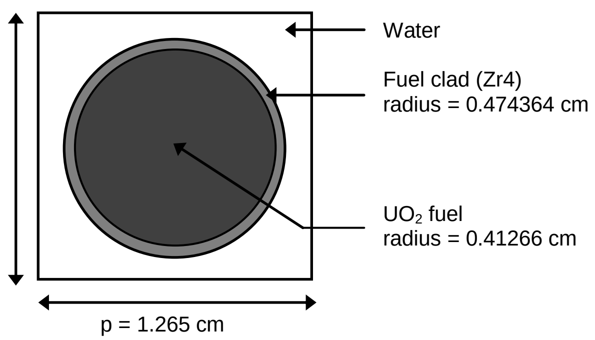
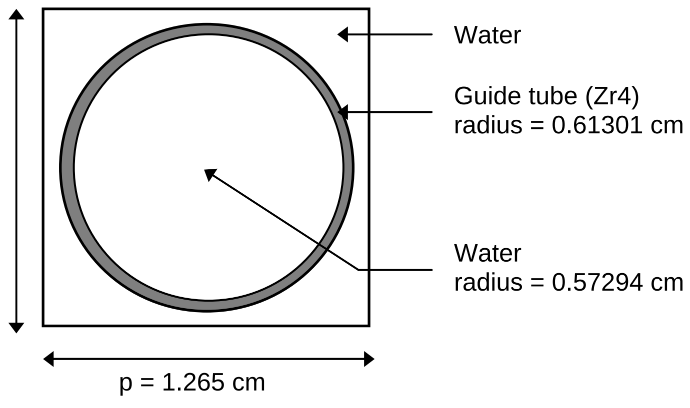


Figure A.3. Guide tube geometry



Figures A.4 and A.5 show top and side views of the cask model. A vertical cross-section through the basket compartment illustrated in Figure A.6 shows the fuel rod and assembly geometry regions, including active fuel, rod endplugs, and assembly upper and lower hardware.

Figure A.4. Cask model (top view)

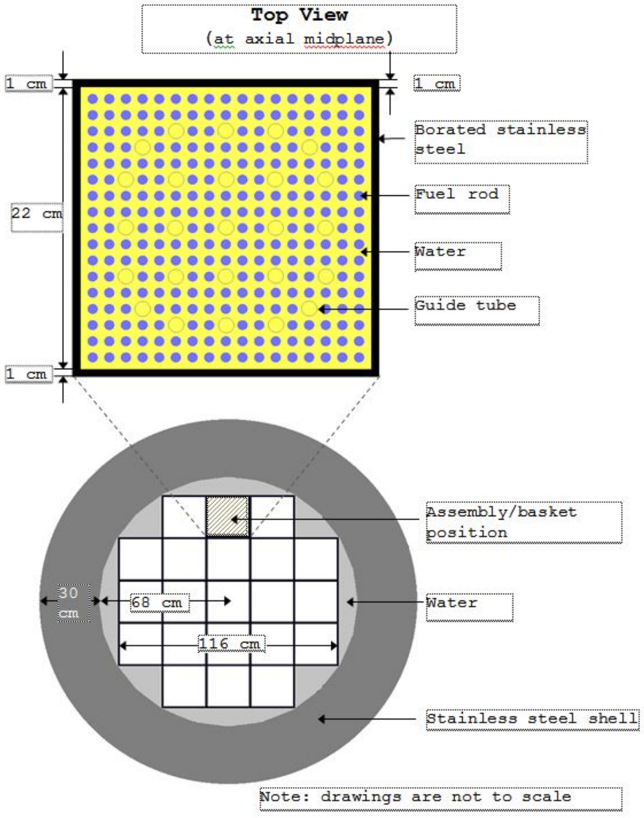


Figure A.5. Cask model (side view)

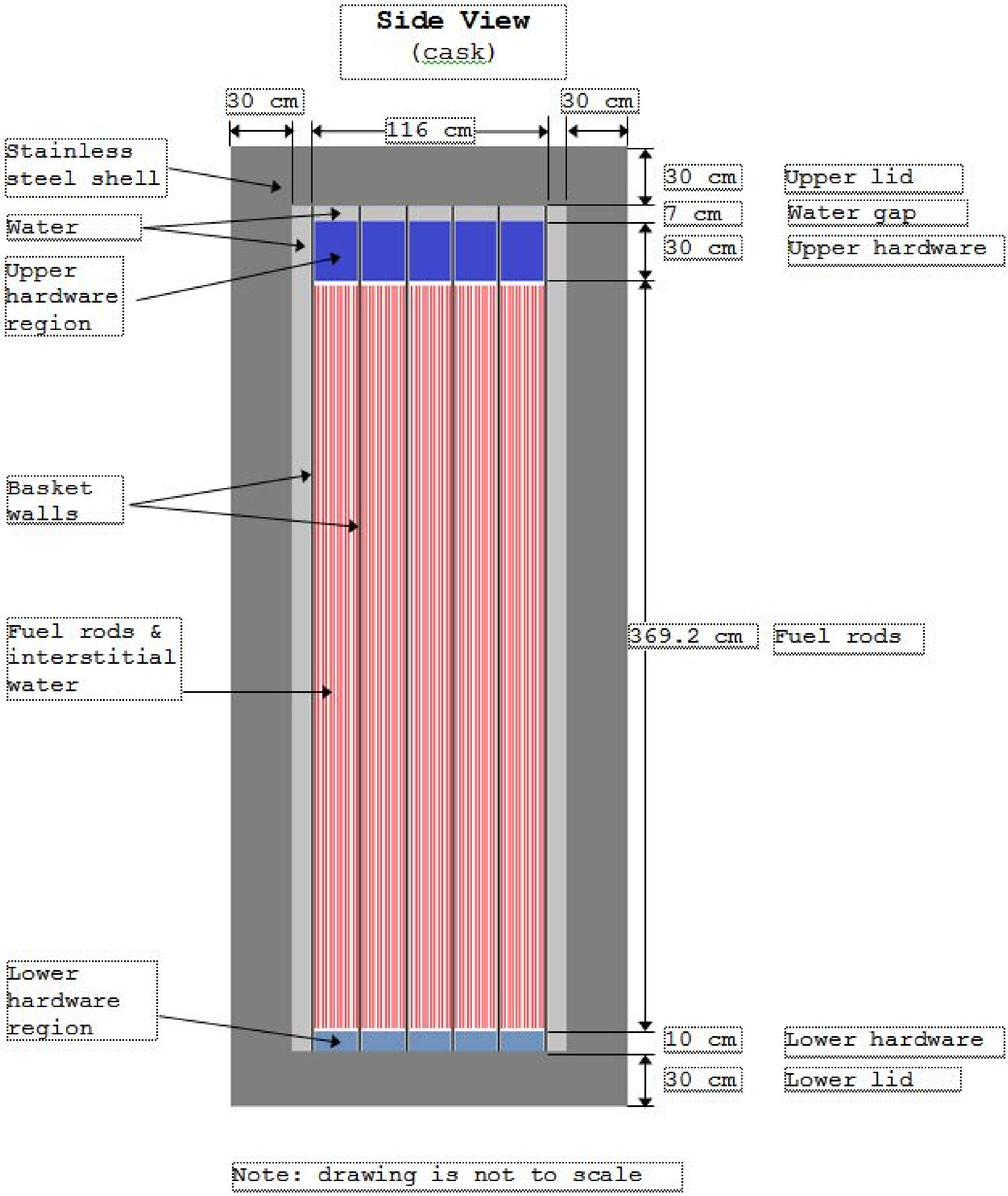
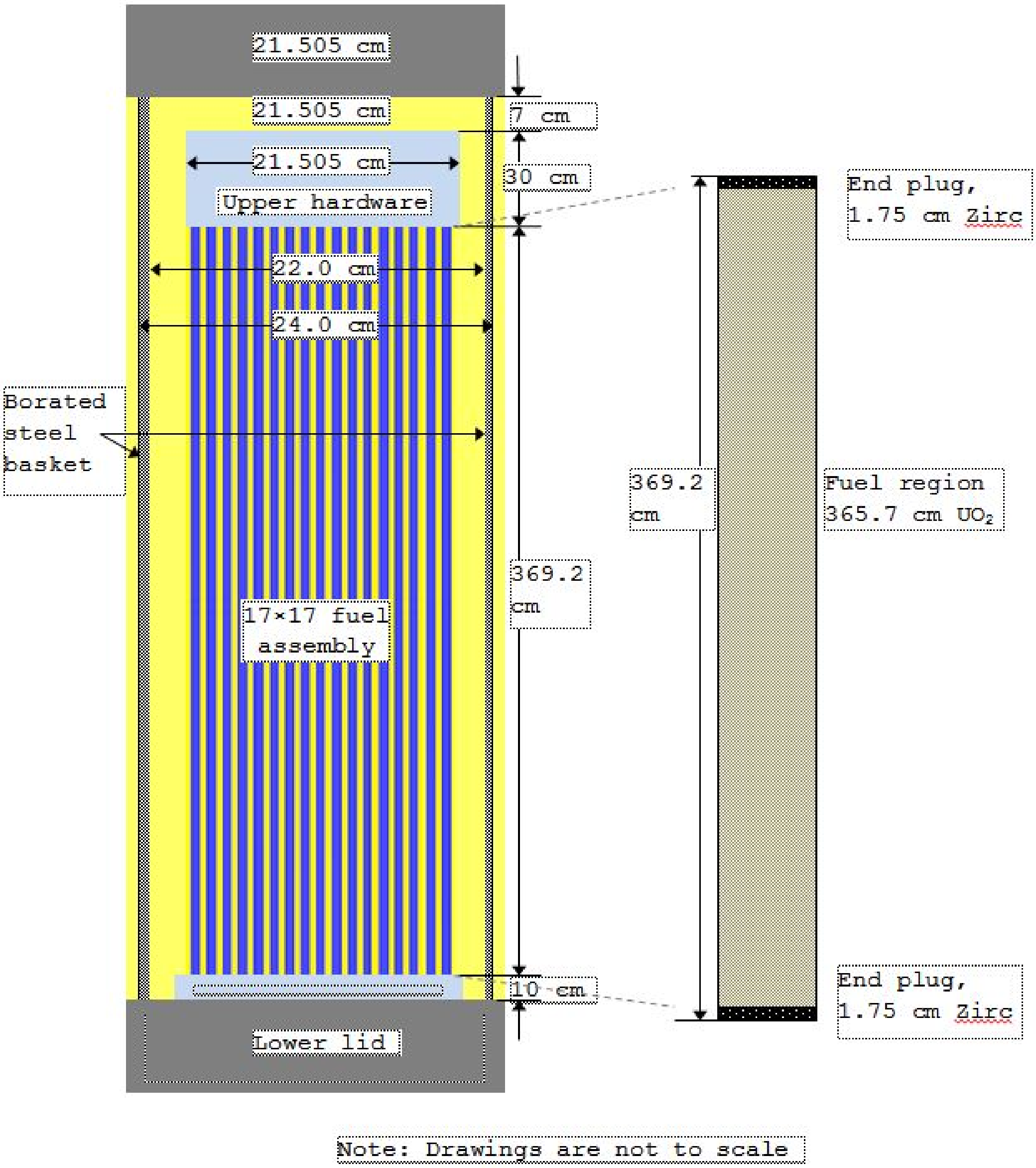


Figure A.6. Single basket compartment



Material and geometrical descriptions

Fuel assembly

Fuel rod data

Rod pitch	1.265 cm
Rod length	365.7 cm (active fuel and guide tube)
Endplug material	Zircaloy 4
Endplug height	1.75 cm
Full rod length	369.2 cm (fuel + 2 endplug)
Radial dimensions	See Figure A.2.

Assembly data

Lattice	17 × 17 (264 fuel rods, 25 guide tubes) (See Figure A.1)
Dimensions	21.505 × 21.505 × 409.2 cm^3
Moderator	Water
Guide tube radial dimensions	See Figure A.3.
Upper and lower end hardware	50% stainless steel, 50% water (by volume) (Note: The assembly upper and lower end hardware will be modeled as a region of smeared water and stainless steel; other hardware, such as grid spacers, is ignored).
Upper hardware height	30.0 cm
Lower hardware height	10.0 cm
Upper water region height	7.0 cm
Lower water region	0.0 cm

Cask

Cask shell

Inner diameter	136.0 cm
Outer diameter	196.0 cm
Material	Stainless steel (SS304)
Total height	476.2 cm
Inner cavity height	416.2 cm

Assembly basket

Inner basket compartment dimensions	22 × 22 × 416.2 cm^3
Material	Borated stainless steel (1 wt% boron)
Basket wall thickness	1 cm

Configuration

21 assemblies positioned in a 5 × 5 array (without assembly in corner).
Fuel assemblies are centered within basket region.
Cask is completely flooded with water. The temperature for cask components is 293K.

3.2. Material compositions

The criticality calculations will use spent fuel compositions from decay calculations (see Section 2) and the nuclide densities, in atom/barn·cm, for the other assembly and cask materials provided in this section.

Fresh fuel	^{234}U	9.5013E-06
	^{235}U	1.0916E-03
	^{236}U	5.0726E-06
	^{238}U	2.2859E-02
	^{16}O	4.7923E-02

Spent fuel

Spent fuel compositions corresponding to the time cases listed in Table A.2 will include:
1) actinide-only cases: ^{16}O and the nuclides identified as“Set 1”in Table A.3.
2) actinides + fission products cases: ^{16}O and the nuclides identified as“Set 2 ” in Table A.3.

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Fuel clad	Fe	1.383E-04
	Cr	7.073E-05
	O	2.874E-04
	Zr	3.956E-02
End plug	Cr	7.589E-05
	Fe	1.484E-04
	Zr	4.298E-02
Guide tube	Fe	1.476E-04
	Cr	7.549E-05
	O	3.067E-04
	Zr	4.222E-02
Water	H	6.662E-02
	O	3.331E-02
Stainless steel	Cr	1.743E-02
	Mn	1.736E-03
	Fe	5.936E-02
	Ni	7.721E-03
Borated (1 wt%) stainless steel	Cr	1.691E-02
	Mn	1.684E-03
	Fe	5.758E-02
	Ni	7.489E-03
	^{10}B	7.836E-04
	^{11}B	3.181E-03
50/50 stainless steel/water mixture	Cr	8.714E-03
	Mn	8.682E-04
	Fe	2.968E-02
	Ni	3.860E-03
	H	3.338E-0
	O	1.669E-02

4. Parameters required

4.1. Fuel compositions

Provide atom densities, in atom/barn·cm, for the light element, actinide, and fission product nuclides designated as benchmark nuclides in Table A.1 for each of the time case numbers listed in Table A.2. The reported values will contain four significant digits.

4.2. k_{eff} calculations

Provide k_{eff} values for fresh fuel and isotopic compositions from the decay calculations for cases involving only the actinides and cases involving both the actinides and the fission products. The total number of k_{eff} calculation cases is 61 (1 fresh fuel composition + 30 decay-time steps × 2 burn-up-credit nuclide sets). Standard deviation values will be reported for the k_{eff} values calculated using a Monte Carlo transport code. The reported values should contain four significant digits.

Criticality calculation cases 1 will use fresh fuel isotopic composition.

Criticality calculation cases 2 through 31 (see Set 1 in Table A.3) will use isotopic compositions that contain actinides only and correspond to decay time case numbers 1 though 30, respectively.

Criticality calculation cases 32 through 61 will use isotopic compositions that contain actinides and fission products (see Set 2 in Table A.3) and correspond to decay time case numbers 1 though 30, respectively.

5. Requested information and results

Forward the results via e-mail to the benchmark coordinator, John Wagner (wagnerjc@ornl.gov). The results should be provided in two files according to the format instructions provided below.

5.1. Spent fuel composition results

The "spent fuel composition results" file must be composed of:

Line No.	Contents
1	"PWR assembly: 4.5 wt% ^{235}U enrichment and 50 GWd/MTU burn-up"
2	Date
3	Institute
4	Contact person
5	E-mail address or telefax number of the contact person
6	Computer code
7	*Time case 2*
8	Nuclide density (atom/barn·cm) of ^{14}C
9	Nuclide density (atom/barn·cm) of ^{36}Cl
10	Nuclide density (atom/barn·cm) of ^{41}Ca
11	Nuclide density (atom/barn·cm) of ^{59}Ni
12	Nuclide density (atom/barn·cm) of ^{79}Se
13	Nuclide density (atom/barn·cm) of ^{93}Zr
14	Nuclide density (atom/barn·cm) of ^{90}Sr
15	Nuclide density (atom/barn·cm) of ^{93m}Nb
16	Nuclide density (atom/barn·cm) of ^{94}Nb
17	Nuclide density (atom/barn·cm) of ^{93}Mo
18	Nuclide density (atom/barn·cm) of ^{95}Mo
19	Nuclide density (atom/barn·cm) of ^{99}Tc
20	Nuclide density (atom/barn·cm) of ^{101}Ru
21	Nuclide density (atom/barn·cm) of ^{103}Rh
22	Nuclide density (atom/barn·cm) of ^{107}Pd
23	Nuclide density (atom/barn·cm) of ^{109}Ag
24	Nuclide density (atom/barn·cm) of ^{126}Sn
25	Nuclide density (atom/barn·cm) of ^{126}Sb
26	Nuclide density (atom/barn·cm) of ^{126m}Sb
27	Nuclide density (atom/barn·cm) of ^{129}I
28	Nuclide density (atom/barn·cm) of ^{133}Cs
29	Nuclide density (atom/barn·cm) of ^{135}Cs
30	Nuclide density (atom/barn·cm) of ^{137}Cs
31	Nuclide density (atom/barn·cm) of ^{143}Nd
32	Nuclide density (atom/barn·cm) of ^{145}Nd
33	Nuclide density (atom/barn·cm) of ^{147}Sm
34	Nuclide density (atom/barn·cm) of ^{149}Sm
35	Nuclide density (atom/barn·cm) of ^{150}Sm
36	Nuclide density (atom/barn·cm) of ^{151}Sm
37	Nuclide density (atom/barn·cm) of ^{152}Sm
38	Nuclide density (atom/barn·cm) of ^{151}Eu
39	Nuclide density (atom/barn·cm) of ^{153}Eu
40	Nuclide density (atom/barn·cm) of ^{155}Gd
41	Nuclide density (atom/barn·cm) of ^{210}Pb
42	Nuclide density (atom/barn·cm) of ^{226}Ra
43	Nuclide density (atom/barn·cm) of ^{228}Ra
44	Nuclide density (atom/barn·cm) of ^{227}Ac
45	Nuclide density (atom/barn·cm) of ^{229}Th
46	Nuclide density (atom/barn·cm) of ^{230}Th
47	Nuclide density (atom/barn·cm) of ^{232}Th
48	Nuclide density (atom/barn·cm) of ^{231}Pa
49	Nuclide density (atom/barn·cm) of ^{232}U
50	Nuclide density (atom/barn·cm) of ^{233}U
51	Nuclide density (atom/barn·cm) of ^{234}U
52	Nuclide density (atom/barn·cm) of ^{235}U
53	Nuclide density (atom/barn·cm) of ^{236}U
54	Nuclide density (atom/barn·cm) of ^{238}U
55	Nuclide density (atom/barn·cm) of ^{237}Np

56	Nuclide density (atom/barn·cm) of ^{238}Pu
57	Nuclide density (atom/barn·cm) of ^{239}Pu
58	Nuclide density (atom/barn·cm) of ^{240}Pu
59	Nuclide density (atom/barn·cm) of ^{241}Pu
60	Nuclide density (atom/barn·cm) of ^{242}Pu
61	Nuclide density (atom/barn·cm) of ^{241}Am
62	Nuclide density (atom/barn·cm) of ^{242m}Am
63	Nuclide density (atom/barn·cm) of ^{243}Am
64	Nuclide density (atom/barn·cm) of ^{245}Cm
65	Nuclide density (atom/barn·cm) of ^{246}Cm
66	*Time case 3*
67 to 124	As for items 8 to 65
125	*Time case 4*
126 to 183	As for items 8 to 65
184	*Time case 5*
185 to 242	As for items 8 to 66
243	*Time case 6*
244 to 301	As for items 8 to 65
302	*Time case 7*
303 to 360	As for items 8 to 65
361	*Time case 8*
362 to 419	As for items 8 to 65
420	*Time case 9*
421 to 478	As for items 8 to 65
479	*Time case 10*
480 to 537	As for items 8 to 65
538	*Time case 11*
539 to 596	As for items 8 to 65
597	*Time case 12*
598 to 655	As for items 8 to 65
656	*Time case 13*
657 to 714	As for items 8 to 65
715	*Time case 14*
716 to 773	As for items 8 to 65
774	*Time case 15*
775 to 832	As for items 8 to 65
833	*Time case 16*
834 to 891	As for items 8 to 65
892	*Time case 17*
893 to 950	As for items 8 to 65
951	*Time case 18*
952 to 1009	As for items 8 to 65
1010	*Time case 19*
1011 to 1068	As for items 8 to 65
1069	*Time case 20*
1070 to 1127	As for items 8 to 65
1128	*Time case 21*
1129 to 1186	As for items 8 to 66
1187	*Time case 22*
1188 to 1245	As for items 8 to 66
1246	*Time case 23*
1247 to 1304	As for items 8 to 65
1305	*Time case 24*
1306 to 1363	As for items 8 to 65
1364	*Time case 25*
1365 to 1422	As for items 8 to 65
1423	*Time case 26*
1424 to 1481	As for items 8 to 65
1482	*Time case 27*

1483 to 1540	As for items 8 to 65
1541	*Time case 28*
1542 to 1599	As for items 8 to 65
1600	*Time case 29*
1601 to 1658	As for items 8 to 65
1659	*Time case 30*
1660 to 1717	As for items 8 to 65
1718	Please describe your analysis environment here. It will be included in the benchmark report. The description should include: Institute and country, participants, Decay data library, Nuclear data processing code or method, Description of your code system, Omitted nuclides if any, Omitted cases if any, Other related information.

5.2. k_{eff} values

The "keff results" file must be composed of:

Line No.	Contents
1	"keff calculation"
2	Date
3	Institute
4	Contact person
5	E-mail address or Telefax Number of the contact person
6	Computer code
7	"actinide only"
8	k_{eff} ("±" standard deviation, if applicable) value for fresh fuel
9 to 38	k_{eff} ("±" standard deviation, if applicable) values for cases 1 through 30 (see Section 4.2 for case description).
39	"actinides + fission products"
40	k_{eff} ("±" standard deviation, if applicable) value for fresh fuel
41 to 70	k_{eff} ("±" standard deviation, if applicable) values for cases 31 through 60 (see Section 4.2 for case description).
71	Please describe your analysis environment here. It will be included in the benchmark report. The description should include: Institute and country, Participants, Description of your code system, Neutron data library, Neutron data processing code or method, Neutron energy groups, Geometry modeling (3-D, 2-D etc.), Omitted nuclides if any, Omitted cases if any, Other related information.

6. Schedule

June 2009	Participants provide results to benchmark co-ordinator
September 2009	Distribution of draft benchmark report
December 2009	All comments on draft report received by benchmark co-ordinator
April 2010	Final draft of benchmark report for Nuclear Science Committee

Appendix B. Participants and methods of analysis

1. VUJE a.s., Slovak Republic

Country: Slovak Republic
Organisation: Nuclear Power Plant Research Institute Trnava Inc (VUJE a.s.)
Participant: Vladimír Chrapčiak

Decay calculations

Description of your code system: SCALE 5.1/ORIGEN-S [1]
Decay data library: SCALE 5.1 decay library based on ENDF/B-VI
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
Decay calculations have been carried out with the ORIGEN-S module. Initial state is fuel composition for assembly with burn-up 50 GWd/MTU, which means no irradiation calculation, only decay calculation. In OrigenArp was chosen "Activation Mode" and library "act_w17x17".

Criticality calculations

Description of your code system: SCALE 5.1/KENO-VI
Neutron data library: SCALE 44GROUPNDF5 based on ENDF/B-V
Neutron data processing code or method: AMPX, CENTRM
Omitted nuclides if any: none
Omitted cases if any: none

Other related information:
k_{eff} calculations have been carried out with the CSAS26 module. The continuous energy (the CENTRM module, library 44GROUPNDF5) and the KENO VI module were used. The number 1 000 000 particles was used (4000 neutrons per generation, 260 generations, and 10 skipped generations).

1. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I–III, February 2009; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.

2. ORNL, United States

Country: United States
Organisation: Oak Ridge National Laboratory
Participant: Georgeta Radulescu

Decay calculations

Decay data library: SCALE 6.1 decay library based on ENDF/B-VII
Description of your code system: SCALE 6.1/ORIGEN-S (beta) [1]
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Criticality calculations

Neutron data library: SCALE ENDF/B-VII.0 continuous energy
Neutron data processing code or method: AMPX
Description of your code system: SCALE 6.1/KENO-V.a (beta)
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
5 000 neutrons per generation, 1 700 generations, and 100 skipped generations.

1. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I–III, February 2009; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.

3. JAEA, Japan

Country: Japan
Organisation: Japan Atomic Energy Agency (JAEA) Japan
Participants: Kiyoshi Ohkubo, Hiroshi Okuno and Kenya Suyama

Decay calculations

Description of your code system: ORIGEN2.2-UPJ [1]
Decay data library: orlibj33 [2]
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
Half-lives of the following 22 nuclides were replaced with those found in the "Table of Isotopes, 8th Edition"[3]: ^{41}Ca, ^{59}Ni, ^{79}Se, ^{90}Sr, ^{93}Mo, ^{135}Cs, ^{151}Sm, ^{228}Ra, ^{230}Th, ^{232}U, ^{233}U, ^{234}U, ^{236}U, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{244}Pu, ^{236}Np, ^{242m}Am, ^{243}Am, and ^{243}Cm.

ORIGEN2.2-UPJ contains:
- updated source code of ORIGEN2.2 of CCC-0371 to use ORLIBJ32 and ORLIBJ33,
- all original libraries in CCC-0371,
- ORLIBJ32 in NEA-164/03 (but libraries for FBR are revised),
- and ORLIBJ33.

In this package, decay data based on the second version of the JNDC FP library and photon and decay data libraries based on JENDL-3.3 are also included.

Criticality calculations

Description of your code system: MCNP-4C2 [4]
Neutron data library: JENDL3.3
Neutron data processing code or method: NJOY99r2
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

1. *ORIGEN2.2-UPJ, A complete package of ORIGEN2 libraries based on JENDL-3.2 and JENDL-3.3*; available from Nuclear Energy Agency Data Bank as NEA-1642.
2. Katakura, J. *et al*., "A Set of ORIGEN2 Cross Section Libraries Based on JENDL-3.3 Library: ORLIBJ33," *JAERI-Data/Code 2004-015*, Japan Atomic Energy Research Institute [in Japanese] (2004).
3. *Table of Isotopes*, Eight Edition, R.B. Firestone, V.S. Shirley, C.M. Baglin, S.Y. Frank Chu and J. Zipkin, Ed., John Wiley & Sons, Inc., New York, NY (1996).
4. *MCNP5/MCNPX: Monte Carlo N-Particle Transport Code System*; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-740.

4. E Mennerdahl Systems, Sweden

Country: Sweden
Organisation: E Mennerdahl Systems
Participant: Dennis Mennerdahl
Sponsor: Swedish Radiation Safety Authority

Decay calculations

Description of your code system: SCALE 6.0/ORIGEN-S [1]
Decay data library: SCALE ENDF/B-VI
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:

Default libraries in ORIGEN-ARP were used. When a nuclide was present in both the light-element library and in the fission-product library, the latter was selected. The radioactive decay was calculated with ORIGEN/S, and the output was prepared by OPUS. The code system is standard SCALE 6 as delivered from the OECD/NEA Data Bank. The pre-compiled Windows version was installed under Windows Vista on a few personal computers, some using Intel and some AMD processors. No benchmarking has been carried out at this site to test the decay libraries, codes, and code options used.

The given atomic densities were converted to gram-atoms, assuming 10^6 grams of the uranium isotopes ^{234}U, ^{235}U, ^{236}U, and ^{238}U. This was intended for ORIGEN/S calculations. The corresponding volume was calculated to be 113,204 cm^3. This was input to OPUS to obtain the requested nuclide densities. There are small deviations between the OPUS nuclide density output for time 0 years and the corresponding specifications for the benchmark. This is probably due to rounding effects. The differences, at most one unit in the last digit, are assumed to be negligible. The OPUS time given for 8 000 years is 8 001 (reason unknown). This makes very small difference in results.

Criticality calculations

Description of your code system: SCALE 6/KENO V.a
Neutron data library: SCALE ENDF/B-VII.0 continuous energy
Neutron data processing code or method: AMPX
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
The code system is standard SCALE 6 as delivered from the OECD/NEA Data Bank. The pre-compiled Windows version was installed under Windows Vista on a few personal computers, some using Intel and some AMD processors. No benchmarking has been carried out at this site to test the decay libraries, codes and code options used. KENO V.a geometry was used without approximations.

1. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I–III, February 2009; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.

5. Universidad Politécnica de Madrid, CSN, and SEA Ingenieria, SL, Spain

Country: Spain
Organisations: Universidad Politécnica de Madrid, CSN, and SEA Ingenieria, SL
Participants: O. Cabellos, B. Cabellos, N. Garcia-Herranz, J. Sanz (Universidad Politécnica de Madrid), Jose M. Conde, C. Alejano (CSN), P. Ortego, C. Tore (SEA Ingenieria, SL)

Decay calculations

Description of your code system: ACAB-2008 [1]
Decay data library: JEFF-3.1 decay data
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Criticality calculations

Transport code: MCNPX-2.5 [2]
Neutron data library: JEFF-3.1.1
Neutron data processing code: NJOY99.259
Neutron energy groups: continue
Geometry modeling: 3D
Omitted Nuclides: none
Omitted cases: none
Other related information: none

Decay calculations

Description of your code system: ACAB-2008
Decay data library: SCALE 6 ORIGEN decay data (ENDF/B-VI)
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Criticality calculations

Transport code: MCNPX-2.5 [2]
Neutron data library: JEFF-3.1.1
Neutron data processing code: NJOY99.259
Neutron energy groups: continue
Geometry modeling: 3D
Omitted nuclides: none
Omitted cases: none
Other related information:
Appendix C includes a summary of the Spanish calculations performed with MCNP and nuclear data ENDFB-VI.

1. *ACAB-2008, ACtivation ABacus Code*; available from Nuclear Energy Agency Data Bank as NEA-1839/01.
2. *MCNP5/MCNPX: Monte Carlo N-Particle Transport Code System*; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-740.

6. AREVA TN International, France

Country: France
Organisation: AREVA TN International (France)
Participants: Marcel Tardy and Aurélien Le Peillet

Decay calculations

Decay data library: JEF 2.2
Description of your code system: DARWIN 2.1 [1]
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Criticality calculations

Neutron data library: JEF 2.2, 172 energy groups
Neutron data processing code or method: AMPX
Description of your code system: CRISTAL V1.0 (APOLLO 2.5.4 and MORET 4.B.2) [2]
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
Probability collision multigroup (APOLLO2) and Monte Carlo multigroup (MORET) 172 groups
Geometry : 2D for APOLLO2 and 3D for MORET

1. A. Tsilanizara *et al*., "DARWIN: an Evolution Code System for a Large Range of Applications", *J. Nucl. Sci. Technol*., Supplement 1, 845 (2003).
2. J.M. Gomit *et al*., "CRISTAL V1: Criticality Package for Burn-up Credit Calculations", *Proceedings of the 7th International Conference on Nuclear Criticality Safety (ICNC2003)*, Tokai-Mura, Japan, 20–24 October 2003, Japan Atomic Energy Agency (2003) (CD-ROM).

7. IRSN, France

Country: France
Organisation: Institut de Radioprotection et de Sûreté Nucléaire (IRSN)
Participants: Wim Haeck, Ludyvine Jutier, Yoann Liegard (PHOENIX decay calculations)
Ludyvine Jutier, Izaskun Ortiz de Echevarria, Julien Thevenin (DARWIN decay and MORET criticality calculations)

Decay calculations

Description of your code system: PHOENIX 1.0.0a beta [1]
Decay data library: standard ORIGEN 2.2 DECAY.LIB decay data library
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
PHOENIX is a standalone point depletion code currently under development at IRSN. The core of PHOENIX is a generic point depletion module that can be tailored to the user's need. The depletion core can be adapted to any type of incident particle (for instance neutrons, protons, etc.) and it is capable of using essentially every reaction type and decay mode (as defined by the ENDF format). The code will have multiple solvers at its disposal to solve the Bateman equations (Taylor series development of the matrix exponential, 4^{th} order Runge Kutta, etc.) in their homogeneous and inhomogeneous form. The 1.0.0a beta of the PHOENIX module is capable of calculating the evolution of materials through radio-active decay and neutron induced activation using ORIGEN 2.2 data libraries. The main solver used for the results reported here is a 4^{th} order Runge Kutta method. The code used (PHOENIX) is still under development and has not been validated yet.

Decay calculations

Description of your code system: DARWIN 2.0
Decay data library: JEF-2
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
Code system: analytical method + Runge-Kutta numerical method (4^{th} order)

Criticality calculations

Description of your code system: MORET5 [2]
Neutron data library: JEFF3.1, continuous energy
Neutron data processing code or method: NJOY99.259 (ACE files)
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
The MORET code is a three dimensional Monte Carlo criticality code. It allows the use of macroscopic cross-sections (obtained from a cell code, APOLLO2 for instance) or more recently the use of punctual cross-sections. Punctual cross-sections have been used for the benchmark. This type of calculation is still under development and has not been validated yet.

1. L. Cousin, W. Haeck and B. Cochet, "Validating the Vesta Monte Carlo Depletion Interface Using Ariane Chemical Assay Data For Pressurized Water Reactor Applications", *Proceedings of PHYSOR 2010 – Advances in Reactor Physics to Power the Nuclear Renaissance*, Pittsburgh, PA, USA, 9-14 May 2010, American Nuclear Society (2010) (CD-ROM).

2. J. Miss *et al.*, "Using Various Point Wise Multi-group Cross Section Libraries in MORET Criticality Calculations", *Proceedings of the International Conference on Nuclear Data for Science and Technology (ND2007)*, Nice, France, 22-27 April 2007, Commissariat à l'Énergie Atomique (2007) (CD-ROM).

8. GRS, Germany

Country : Germany
Organisation: Gesellschaft für Anlagen–und Reaktorsicherheit (GRS) mbH
Participants: M. Wagner, R. Kilger, U. Hesse and M. Behler

Decay calculations

Description of your code system: ORIGEN-X-2008 [1]
Decay data library: ENDF/B-VI decay data
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
ORIGEN-X-2008 so far has been used for activation calculations and is now also being tested for the long time decay. In the present benchmark, small deviations might occur due to the choice of large time steps in connection to the approximation concerning short-lived isotopes in the calculation procedure. The current version of ORIGEN-X-2008 only supports 10 decay steps, and several runs had to be performed to get the results. The chosen time steps are the most straightforward ones and have not been optimised to circumvent the approximation; therefore, some deviations might appear for some of the nuclides under consideration (e.g. ^{237}Np, ^{233}U, ^{229}Th, ^{230}Th). The first run used the first 10 time steps as given, the second run started with 150 years as the first time step, and in the third run 20 000 years was used as the first decay step. The problem with that approximation has been solved by now.

Criticality calculations

Description of your code system: SCALE 6.0/KENO-V.a [2]
Neutron data library: Scale 6, ENDFB-VII 238 groups
Neutron data processing code or method: AMPX
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
The number of neutrons per generation was chosen to be 50 000 neutrons, and the calculation was stopped when a standard deviation of 5e-5 was achieved.

1. U. Hesse, K. Hummelsheim and E. Moser, "Validierungsprogramm fuer GRS-ORIGEN-X," Technical Report (2005) (not yet published).
2. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I–III, February 2009; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.

9. Nuclear Research Institute at Rez, Czech Republic

Country: Czech Republic
Organisation: Nuclear Research Institute at Rez
Participant: Frantisek Havluj

Decay calculations

Description of your code system: SCALE 6.0/ORIGEN-S [1]
Decay data library: SCALE 6 ORIGEN library
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Criticality calculations

Description of your code system: SCALE 6/KENO-V.a
Neutron data library: Scale 6, ENDFB-VII.0 238 energy groups
Neutron data processing code or method: AMPX
Omitted nuclides if any: none
Omitted cases if any: none

Other related information
3-D modeling fully as described in the benchmark specification; KENO V in CSAS5 sequence; CENTRM for resonance processing

Criticality calculations

Description of your code system: SCALE 6.0/KENO-V.a
Neutron data library: Scale 6, ENDFB-VII.0 continuous energy
Neutron data processing code or method: AMPX
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
3-D modelling fully as described in the benchmark specification; KENO V.a in CSAS5 sequence.

1. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I–III, February 2009; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.

10. VTT Technical Research Centre of Finland, Finland

Country: Finland
Organisation: VTT Technical Research Centre of Finland
Participants: Karin Rantamäki and Markku Anttila

Decay calculations

Description of your code system: SCALE 6.0/ORIGEN-S [1]
Decay data library: SCALE 6 ORIGEN library
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Criticality calculations

Description of your code system: MCNP5, version 5.1.40 [2]
Neutron data library: MCNP 5 V1.40 default (based on ENDF/B-VI)
Neutron data processing code or method:
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
5 000 neutrons per generation; 1 000 generations (300 omitted)
Case 8 of the actinides and fission products series stopped after 977 cycles

1. *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluations*, ORNL/TM-2005/39, Version 6, Vols. I–III, February 2009; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-750.
2. *MCNP5/MCNPX: Monte Carlo N-Particle Transport Code System*; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-740.

11. KFKI Atomic Energy Research Institute, Hungary

Country: Hungary

Organisation: KFKI Atomic Energy Research Institute
Participants: Gabor Hordosy (SCALE decay and MCNP criticality calculations)
Peter Vertes, Aron Brolly, Gabor Hordosy (TIBSO decay calculations)

Organisation: Anandor Ltd.
Participant: Sandor Patai Szabo (SCALE decay and MCNP criticality calculations)

Decay calculations

Description of your code system: SCALE 6.0/ORIGEN-S
Decay data library: SCALE 6.0 ORIGEN library based on ENDF/B-VI
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

Decay calculations

Description of your code system: TIBSO [1, 2]
Decay data library: JEF2.2 decay data
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
Results No. 2 were calculated by TIBSO: Code System for Calculation of Production and Spreading of Radioactive Isotopes, using JEF2.2 nuclear data. TIBSO was developed by Peter Vertes at KFKI Atomic Energy Research Institute, Hungary. It is available also from the NEA Data Bank.

Criticality calculations

Description of your code system: MCNP5 [3]
Neutron data library: MCNP5 continuous energy libraries based on ENDF/B-VI.2 and V
Neutron data processing code or method:
Omitted nuclides if any: none
Omitted cases if any: none
Other related information:
Two sets of MCNP5 criticality calculations were carried out using decay compositions determined with SCALE and TIBSO.

1. *TIBSO, Nuclear Transitions and Radioactivity Migration in Technological System*; available from Nuclear Energy Agency Data Bank as NEA-1592/01.
2. P. Vertes, "Multinodal Treatment of Production, Decay and Spreading of Radioactive Isotopes", *Nuclear Technology*, 128, 124 (1999).
3. *MCNP5/MCNPX: Monte Carlo N-Particle Transport Code System*; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as CCC-740.

12. LANL, United States

Country: United States
Organisation: Los Alamos National Laboratory
Participant: Holly Trellue

Decay calculations

Description of your code system: CINDER 90 [1]
Decay data library: ENDF/B-VI
Omitted nuclides if any: none
Omitted cases if any: none
Other related information: none

1. *MONTEBURNS 2.0, An Automated, Multi-Step Monte Carlo Burnup Code System*; available from Radiation Safety Information Computational Center at Oak Ridge National Laboratory as PSR-455.

Appendix C. k_{eff} comparisons with ENDF/B-VI and JEFF-3.1.1 cross-section data for only actinide and actinide plus fission products

contributed by
Universidad Politécnica de Madrid, CSN, and SEA Ingenieria, SL, Spain

In this study criticality calculations are performed for a representative PWR cask model utilising the PWR spent fuel isotopic compositions from the decay calculations for nuclides relevant to burn-up credit corresponding to the times listed in Table C.1.

The geometric data of the PWR fuel assembly and PWR cask and the initial 4.5 wt% ^{235}U enrichment composition are given in [C.1].

Table C.1. Timesteps for k_{eff} calculation

Time case number	Time (Years)	Time case number	Time (Years)
1	0	16	1 000
2	1	17	2 000
3	2	18	5 000
4	5	19	8 000
5	10	20	10 000
6	20	21	15 000
7	40	22	20 000
8	60	23	25 000
9	80	24	30 000
10	100	25	40 000
11	120	26	45 000
12	150	27	50 000
13	200	28	100 000
14	300	29	500 000
15	500	30	1 000 000

The study is performed with MCNPX 2.4.0 code and ENDF/B-VI cross sections. First comparison in k_{eff} is performed between isotopic concentrations obtained with ACAB code by using ORIGEN2.2 and JEFF-3.1.1 decay constants with both actinide-only and actinide plus fission products.

Second comparison is performed between ENDF/B-VI and JEFF-3.1.1 cross section libraries by using the isotopic concentrations obtained with ACAB code with JEFF-3.1.1 library, for both actinide-only and actinide and fission products cases.

The three sets of calculated k_{eff} values for the corresponding decay times for actinide-only cases are presented in Table C.2 and graphically in Figure C.1.

The three sets of calculated k_{eff} values for the corresponding decay times for actinide plus fission products are presented in Table C.3 and graphically in Figure C.2.

Additionally, the two sets of differences on k_{eff} are presented in Table C.4 and graphically in Figure C.3.

Table C.2. k_{eff} calculated values with ENDFBVI and JEFF-3.1.1 libraries for actinide-only case

ORIGEN2.2 Isotope with ENDF/B-VI		JEFF-3.1.1 Isotope with ENDF/B-VI		JEFF-3.1 Isotope with JEFF-3.1.1 Library	
k_{eff}	STD	k_{eff}	STD	k_{eff}	STD
1.14631	0.00053	1.14631	0.00053	1.15057	0.00035
0.95316	0.00045	0.95228	0.00050	0.95819	0.00033
0.94859	0.00052	0.94880	0.00050	0.95329	0.00033
0.94384	0.00051	0.94376	0.00049	0.94786	0.00033
0.92992	0.00049	0.92982	0.00052	0.93350	0.00034
0.91038	0.00050	0.91030	0.00049	0.91440	0.00033
0.88486	0.00049	0.88382	0.00048	0.88710	0.00032
0.85905	0.00045	0.85944	0.00046	0.85921	0.00031
0.84939	0.00046	0.85035	0.00047	0.85095	0.00032
0.84759	0.00047	0.84858	0.00047	0.84917	0.00032
0.84719	0.00046	0.84851	0.00047	0.84925	0.00031
0.84934	0.00046	0.84983	0.00047	0.85054	0.00031
0.85129	0.00048	0.85142	0.00047	0.85353	0.00032
0.85628	0.00048	0.85588	0.00048	0.85760	0.00031
0.86235	0.00047	0.86253	0.00048	0.86558	0.00031
0.87352	0.00049	0.87274	0.00049	0.87778	0.00032
0.89133	0.00048	0.89115	0.00049	0.89625	0.00033
0.90398	0.00049	0.90444	0.00048	0.91181	0.00033
0.91776	0.00049	0.91610	0.00049	0.92266	0.00032
0.92298	0.00047	0.92348	0.00049	0.92941	0.00032
0.92731	0.00048	0.92656	0.00048	0.93233	0.00033
0.93192	0.00048	0.93178	0.00048	0.93943	0.00032
0.93612	0.00048	0.93657	0.00048	0.94174	0.00032
0.93605	0.00047	0.93622	0.00047	0.94243	0.00032
0.93742	0.00047	0.93548	0.00047	0.94187	0.00031
0.93198	0.00047	0.93200	0.00046	0.93703	0.00031
0.92727	0.00049	0.92841	0.00047	0.93360	0.00031
0.92510	0.00047	0.92546	0.00048	0.93115	0.00031
0.90629	0.00047	0.90709	0.00046	0.91308	0.00031
0.90624	0.00046	0.90616	0.00047	0.91184	0.00031
0.90796	0.00047	0.90785	0.00046	0.91407	0.00031

Table C.3. The calculated k_{eff} values with ENDF/B-VI and JEFF3.1.1 cross-section data for actinide and fission product case

ORIGEN2.2 Isotope with ENDF/B-VI		JEFF-3.1 Isotope with ENDF/B-VI		JEFF-3.1 Isotope with JEFF-3.1.1 Library	
k_{eff}	STD	k_{eff}	STD	k_{eff}	STD
1.14631	0.00053	1.14631	0.00053	1.15057	0.00035
0.86062	0.00047	0.85890	0.00049	0.86269	0.00032
0.84960	0.00048	0.85065	0.00047	0.85186	0.00031
0.84274	0.00047	0.84316	0.00047	0.84517	0.00031
0.82737	0.00045	0.82616	0.00046	0.82863	0.00031
0.80680	0.00046	0.80563	0.00046	0.80699	0.00030
0.77973	0.00047	0.78076	0.00045	0.78047	0.00030
0.75644	0.00043	0.75493	0.00043	0.75546	0.00029
0.74832	0.00044	0.74782	0.00044	0.74772	0.00029
0.74487	0.00043	0.74498	0.00043	0.74462	0.00029
0.74422	0.00044	0.74455	0.00044	0.74419	0.00029
0.74500	0.00043	0.74462	0.00044	0.74570	0.00029
0.74763	0.00044	0.74598	0.00044	0.74621	0.00029
0.74763	0.00044	0.74802	0.00044	0.74871	0.00029
0.75298	0.00045	0.75161	0.00043	0.75358	0.00030
0.75849	0.00044	0.75850	0.00044	0.76009	0.00029
0.76696	0.00044	0.76770	0.00046	0.77037	0.00030
0.77506	0.00045	0.77375	0.00045	0.77891	0.00029
0.78204	0.00044	0.78159	0.00044	0.78513	0.00030
0.78466	0.00044	0.78474	0.00045	0.78934	0.00029
0.78646	0.00045	0.78750	0.00044	0.79047	0.00030
0.78932	0.00044	0.78914	0.00045	0.79248	0.00029
0.78874	0.00044	0.78870	0.00043	0.79232	0.00029
0.78731	0.00045	0.78693	0.00043	0.79061	0.00029
0.78344	0.00043	0.78391	0.00044	0.78699	0.00029
0.77590	0.00044	0.77692	0.00043	0.77909	0.00029
0.77174	0.00042	0.77185	0.00043	0.77480	0.00028
0.76794	0.00043	0.76845	0.00044	0.77062	0.00029
0.74728	0.00041	0.74822	0.00042	0.74977	0.00028
0.74992	0.00041	0.74896	0.00043	0.75173	0.00027
0.75336	0.00043	0.75408	0.00043	0.75734	0.00028

Table C.4. Differences between calculated k_{eff} for the three combinations of decay data library and cross-section library

Time (Years)	(JEF(JEF)-JEFF(EN6))Ac	(JEF(JEF)-JEFF(EN6))Ac+FP	(JEF(EN6)-OR22(EN6))Ac	(JEF(EN6)-ORI22(EN6))Ac+FP
0.1	0.00591	0.00379	-0.00088	-0.00172
1	0.00449	0.00121	0.00021	0.00105
2	0.00410	0.00201	-0.00008	0.00042
5	0.00368	0.00247	-0.00010	-0.00121
10	0.00410	0.00136	-0.00008	-0.00117
20	0.00328	-0.00029	-0.00104	0.00103
40	-0.00023	0.00053	0.00039	-0.00151
60	0.00060	-0.00010	0.00096	-0.00050
80	0.00059	-0.00036	0.00099	0.00011
100	0.00074	-0.00036	0.00132	0.00033
120	0.00071	0.00108	0.00049	-0.00038
150	0.00211	0.00023	0.00013	-0.00165
200	0.00172	0.00069	-0.00040	0.00039
300	0.00305	0.00197	0.00018	-0.00137
500	0.00504	0.00159	-0.00078	0.00001
1 000	0.00510	0.00267	-0.00018	0.00074
2000	0.00737	0.00516	0.00046	-0.00131
5 000	0.00656	0.00354	-0.00166	-0.00045
8 000	0.00593	0.00460	0.00050	0.00008
10 000	0.00577	0.00297	-0.00075	0.00104
15 000	0.00765	0.00334	-0.00014	-0.00018
20 000	0.00517	0.00362	0.00045	-0.00004
25 000	0.00621	0.00368	0.00017	-0.00038
30 000	0.00639	0.00308	-0.00194	0.00047
40 000	0.00503	0.00217	0.00002	0.00102
45 000	0.00519	0.00295	0.00114	0.00011
50 000	0.00569	0.00217	0.00036	0.00051
100 000	0.00599	0.00155	0.00080	0.00094
500 000	0.00568	0.00277	-0.00008	-0.00096
1 000 000	0.00622	0.00326	-0.00011	0.00072

Figure C.1. k_{eff} values for actinide-only case

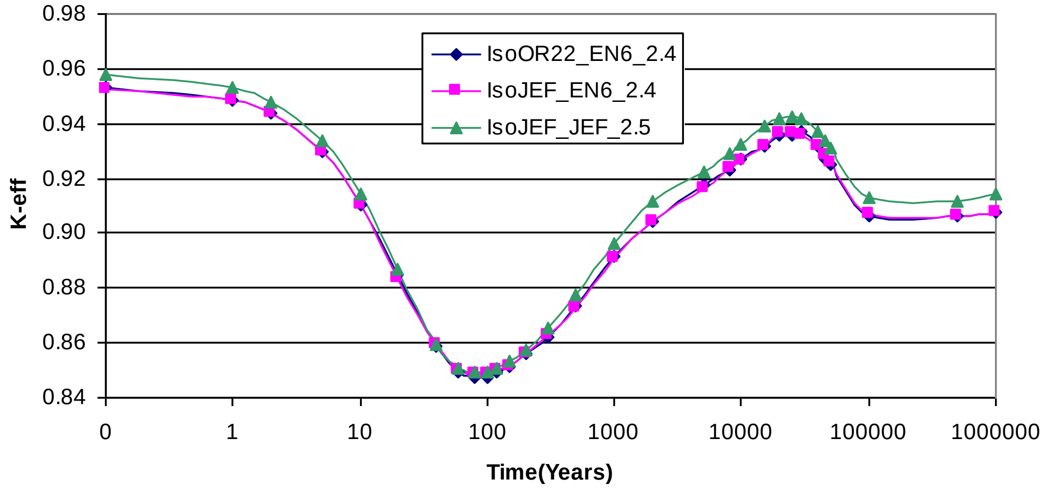


Figure C.2. k_{eff} comparisons for actinide plus fission products case

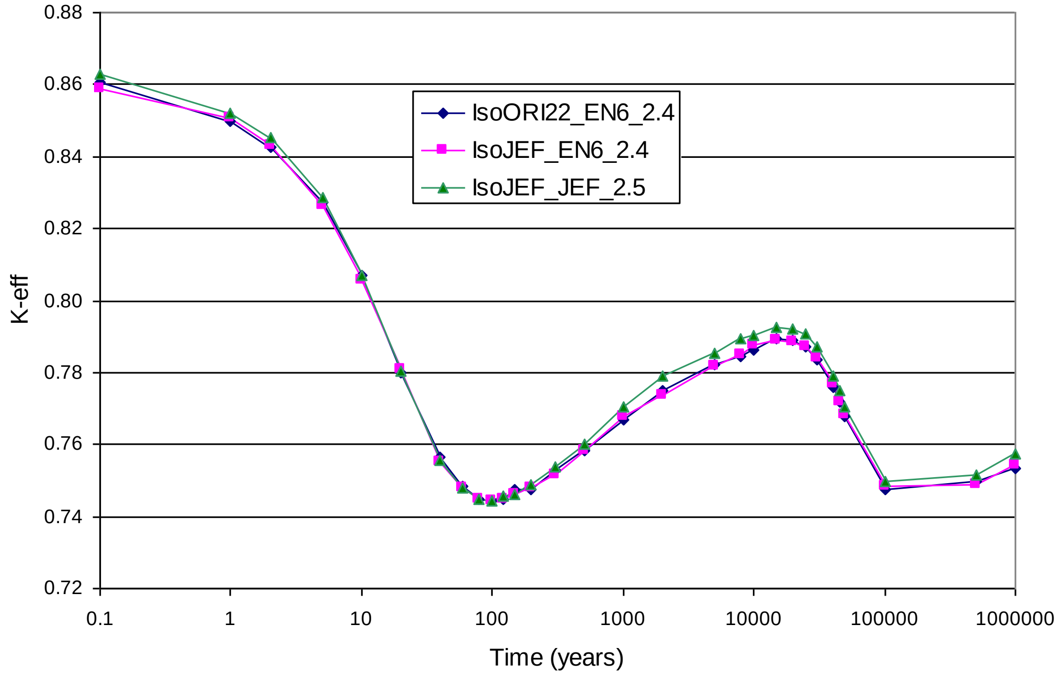
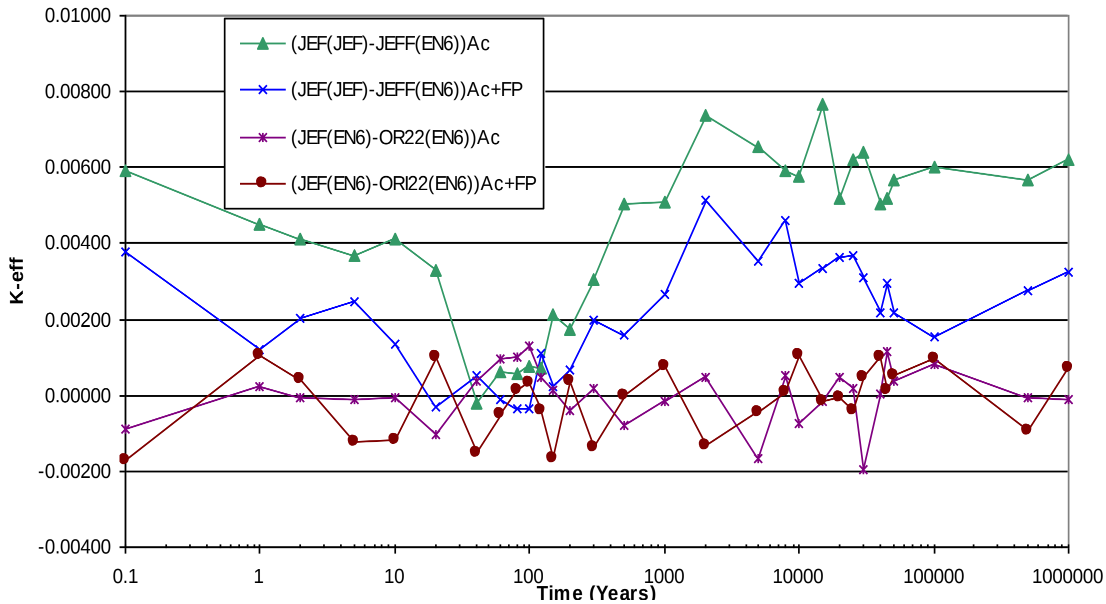


Figure C.3. k_{eff} differences with ENDF/B-VI and JEFF-3.1.1 libraries



[C] J.C. Wagner and G. Radulescu, Specification for Phase VII Benchmark "UO_2 Fuel: Study of Spent Fuel Composition for Long-Term Disposal"; available from www.oecd-nea.org/science/wpncs/buc/specifications/.

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After spent nuclear fuel (SNF) is discharged from a nuclear reactor, fuel composition and reactivity continue to vary as a function of time due to the decay of unstable nuclides. Accurate predictions of the concentrations of long-lived radionuclides in SNF, which represent a significant potential hazard to human beings and to the environment over a very long period, are particularly necessary for radiological dose assessments.

This report assesses the ability of existing computer codes and associated nuclear data to predict isotopic compositions and their corresponding neutron multiplication factor (k_{eff}) values for pressurised-water-reactor (PWR) UO_2 fuel at 50 GWd/MTU burn-up in a generic spent fuel cask configuration. Fuel decay compositions and k_{eff} values have been calculated for 30 post-irradiation time steps out to one million years.

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