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Nuclear energy — Light water reactors — Decay heat power in non-recycled nuclear fuels

Énergie nucléaire — Réacteurs à eau légère — Puissance résiduelle des combustibles nucléaires non recyclés

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 6, *Reactor technology*.

This second edition cancels and replaces the first edition (ISO 10645:1992), which has been technically revised.

The main changes compared to the previous edition are as follows:

— The decay heat curves for ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu are revised using data adopted from the American National Standard ANS-5.1-2014[1].

— These curves are based on fits to experimental spectroscopic and calorimetric measurements of fission product decay heat at short cooling times less than ~10^5 seconds, and on measurements and simulations for longer times[2].

— Nuclear data constants are updated to reflect modern evaluated values.

— The range of initial ^{235}U enrichment is extended beyond 4,1 % (mass fraction) to 5 %.

— Burnup range is extended to 62 GWd/t, an increase from 52 GWd/t in the previous 1992 edition.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The decay heat power of nuclear fuels is the thermal power produced by radioactive decay of fission and activation products of the nuclear fuel. Decay heat is one of the contributors to the total heat emitted from the nuclear fuel during the reactor operation, representing about <7 % of the total heat. As decay heat continues to be released after shutdown of a nuclear reactor, it is an important physical quantity for the design of systems in which the decay heat power should be taken into consideration as a heat source.

This document provides an alternative to dedicated and validated calculation codes, as it provides values for the local generation of decay heat power as a function of the thermal fuel power during operation. The values for the fission product component of decay heat are based on fits to measured data for short cooling times less than ~10^5 s[2], and on measurements and computational simulations for longer times. Values for other components of decay heat are developed to provide conservative estimates. Therefore, at longer cooling times where fission products represent an increasingly smaller relative contribution to total decay heat, this document becomes increasing conservative, and alternative methods such as dedicated computer codes may provide more accurate estimates. The spatial distribution of the energy conversion into heat, e.g. γ-radiation, is not considered. If required, evaluation of this is left to the user.

The calculation procedure used has the advantage of enabling the estimation of the decay heat power without the need for a validated dedicated calculation code. Nevertheless, the calculation requires the fission fractions of each fissile isotope. These values are not given in this document but can be obtained from literature[3][4] or computer codes.

The power generated by residual fission induced by delayed neutrons after shutdown and activated structural materials is not considered in this document. Delayed neutrons are generally negligible several minutes after core shutdown, and the activated structural materials generally have a minor effect on the global decay heat. Analyses of delayed neutron heating is configuration specific and may require more detailed models. Similarly, analysis of structural activation heating requires separate evaluations.

Nuclear energy — Light water reactors — Decay heat power in non-recycled nuclear fuels

1 Scope

This document provides the basis for calculating the decay heat power of non-recycled nuclear fuel of light water reactors. For this purpose the following components are considered:

— the contribution of the fission products from nuclear fission;

— the contribution of the actinides;

— the contribution of isotopes resulting from neutron capture in fission products.

This document applies to light water reactors (pressurized water and boiling water reactors) loaded with a nuclear fuel mixture consisting of ^{235}U and ^{238}U. Application of the fission product contribution to decay heat developed using this document to other thermal reactor designs, including heavy water reactors, is permissible provided that the other contributions from actinides and neutron capture are determined for the specific reactor type. Its application to recycled nuclear fuel, like mixed-oxide or reprocessed uranium, is not permissible.

The calculation procedures apply to decay heat periods from 0 s to 10^9 s.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
decay heat power
thermal power produced by radioactive decay of fission and activation products of the nuclear fuel, following shutdown of a nuclear fission reactor, excluding prompt radiation emissions

3.2
operating time
entire period of irradiation from the first loading of the considered fuel into the reactor until the final shutdown and removal of the fuel

3.3
decay time
time elapsing after the *operating time* (3.2)

3.4
power histogram
approximation of the true continuous variation of power with time, by subdividing the variation into intervals of constant power output

4   Symbols and subscripts

4.1   Symbols

Table 1 shows the symbols used in this document.

Table 1 — Symbols

Symbol	Quantity	Unit
$A(t)$	Factor to be applied to the decay heat power of the fission products P, for calculating the contribution P_A of the actinides (excluding ^{239}U and ^{239}Np)	Unitless
$f_i(t)$	Decay heat power of the fission products at time t after a single nuclear fission of the fissile nuclide i	(MeV/s)/fission
$\Delta f_i(t)$	Standard deviation of $f_i(t)$	(MeV/s)/fission
$F_i(t_k,T_k)$	Decay heat power of the fission products of the fissile nuclide i at time t, after the irradiation time interval, T_k, referred to one fission per second	(MeV/s)/(fission/s)
$\Delta F_i(t_k,T_k)$	Standard deviation of $F_i(t)$	(MeV/s)/(fission/s)
$H(t)$	Factor to be applied to the decay heat power of the fission products P, for calculating the contribution P_E from neutron capture in fission products (excluding capture in ^{133}Cs)	Unitless
P_k	Total thermal power of the fuel during the kth time interval T_k	a
P_{ik}	Contribution of the fissile nuclide i to the thermal power of the fuel during the kth time interval T_k	b
$P_N(t,T)$	Total decay heat power at time t after the end of operating time, T	b
$P_S(t,T)$	Summed decay heat power on the basis of fission product decays	b
$\Delta P_S(t,T)$	Standard deviation of $P_S(t,T)$	b
$P_{Si}(t,T)$	Contribution of fissile nuclide i to the decay heat power $P_S(t,T)$	b
$\Delta P_{Si}(t,T)$	Standard deviation of $P_{Si}(t,T)$	b
$P_E(t,T)$	Contribution to the decay heat power due to neutron capture in fission products other than ^{133}Cs	b
$P_B(t,T)$	Contribution of actinides ^{239}U and ^{239}Np to the decay heat power	b
$P_A(t,T)$	Contribution of actinides other than ^{239}U and ^{239}Np to the decay heat power	b
$P_{Cs}(t,T)$	Contribution of ^{134}Cs to the decay heat power	b
Q_i	Total thermal energy released from one nuclear fission of the fissile nuclide i	MeV
ΔQ_i	Standard deviation of the thermal energy released from one nuclear fission of the fissile nuclide i	MeV
t	Decay time (see 5.3 and Figure 1)	s
t_k	Time from the end of operating time interval T_k in the power histogram (see Figure 1)	s
T	Operating time (see 5.2 and Figure 1)	s
T_k	Duration of operating time interval k in the power histogram (see Figure 1)	s
T_{eff}	Operating time minus shutdown intervals	s
α_{ij}	Coefficient used for representing the decay heat power of fission products as the summation of 23 exponential functions	(MeV/s)/fission
a Any power unit can be used.		
b Same power unit as P_k.		

Table 1 *(continued)*

Symbol	Quantity	Unit
β_{ij}	Coefficient used for representing the standard deviation of the decay heat power of fission products as the summation of 23 exponential functions	(MeV/s)/fission
λ_{ij}	Exponent used for representing the decay heat power of fission products as the summation of 23 exponential functions	s^{-1}
^a	Any power unit can be used.	
^b	Same power unit as P_k.	

4.2   Subscripts

i   Subscript denoting the fissile nuclides ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

j   Summation subscript used for representing the decay heat power by a summation of exponential functions

k   Subscript used for enumerating the individual time intervals in the power histogram

m   Number of time interval T_k in the power histogram

5   Calculation of decay heat power

5.1   General

To calculate the decay heat power, the following components shall be considered:

— the contribution of the fission products from nuclear fission of the four nuclides ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu (other fissile nuclides shall be treated as ^{235}U);

— the contribution of the actinides;

— the contribution of nuclides resulting from neutron capture in fission products.

The calculation procedures shall apply to the decay heat power for decay times *t* between 0 s and 10^9 s.

Decay heat power from delayed neutron-induced fission and activation in structural materials are not included in this document and shall be evaluated by the user and appropriately included in any analyses of decay heat power.

5.2   Power histogram

Generally, the composition and power output of the fuel under consideration are subject to change during the operating time. This can be taken into account for calculating the decay heat power, by further subdividing the operating time into intervals of constant power and constant fissile nuclide fission rate (constant composition, see Figures 1 and A.1). It shall be ensured that the systematic error introduced by this approximation is taken into account in the estimation of the uncertainty of the decay heat power. This error can be reduced by making the best possible approximation of the fuel power at the end of the operating time. The error introduced by the approximation of the power in the power histogram decreases rapidly with increasing decay time, the accuracy of approximation in the individual intervals can decrease with increasing distance t_k of interval *k* from the decay instant considered. Alternatively, in lieu of performing an uncertainty determination, a conservative calculation may be performed by using the maximum value of the operating power during the irradiation time in the reactor and reducing the irradiation time to preserve the burnup. Any conservative calculations shall be justified by the user.

Since a variation in the relative power contributions of the fissile nuclide is less important for the decay heat power than a variation in the operating power, a rougher scaling is often sufficient for this purpose.

5.3 Contribution of fission products

The contribution $P_S(t,T)$ of the fission products to the decay heat power is calculated from the individual contributions $P_{Si}(t,T)$ of the four fissile isotopes using Formula (1).

$$P_S\left(t,T\right) = \sum_{i=1}^{4} P_{Si}\left(t,T\right) \tag{1}$$

Each contribution $P_{Si}(t,T)$ is in turn composed of the summed decay heat powers of the m time intervals of the power histogram and is calculated as shown in Formula (2).

$$P_{Si}\left(t,T\right) = \sum_{k=1}^{m} P_{Si}\left(t_k,T_k\right) = \sum_{k=1}^{m} \frac{P_{ik}}{Q_i} F_i\left(t_k,T_k\right) \tag{2}$$

where

$\quad P_{ik}$ $\qquad$ is the total thermal power released by the fuel during fission;

$\quad Q_i$ $\qquad$ is the total thermal energy released by a single fission;

$\quad P_{ik}/Q_i$ $\quad$ gives the fission rate of the fissile nuclide i.

$F_i(t_k,T_k)$ is the decay heat power of the fissile nuclide i, referred to one nuclear fission per second, for a time interval of duration T_k and for a decay time t_k. It is calculated from the energy release $f_i(t)$ of the fission products of a single fission at time t after fission as shown in Formula (3).

$$F_i\left(t_k,T_k\right) = \int_{o}^{T_k} f_i\left(T_k - T' + t_k\right) dT' \tag{3}$$

$f_i(t)$ is calculated as shown in Formula (4) using the coefficients a_{ij}, λ_{ij} given in Tables 2, 3, 4, and 5.

$$f_i\left(t\right) = \sum_{j=1}^{23} \alpha_{ij} e^{-\lambda_{ij} t} \tag{4}$$

The following Formula (5) is thus obtained.

$$F_i\left(t_k,T_k\right) = \sum_{j=1}^{23} \frac{\alpha_{ij}}{\lambda_{ij}} \left(1 - e^{-\lambda_{ij} T_k}\right) e^{-\lambda_{ij} t_k} \tag{5}$$

Hence, the contribution $P_S(t,T)$ of the fission products to the decay heat power is calculated using the Formula (6).

$$P_S\left(t,T\right) = \sum_{i=1}^{4} \sum_{k=1}^{m} \left\{ \frac{P_{ik}}{Q_i} \sum_{j=1}^{23} \left[\frac{\alpha_{ij}}{\lambda_{ij}} \left(1 - e^{-\lambda_{ij} T_k}\right) e^{-\lambda_{ij} t_k} \right] \right\} \tag{6}$$

Figure 1 illustrates a power histogram with four time intervals of varying power for the fissile nuclide i.
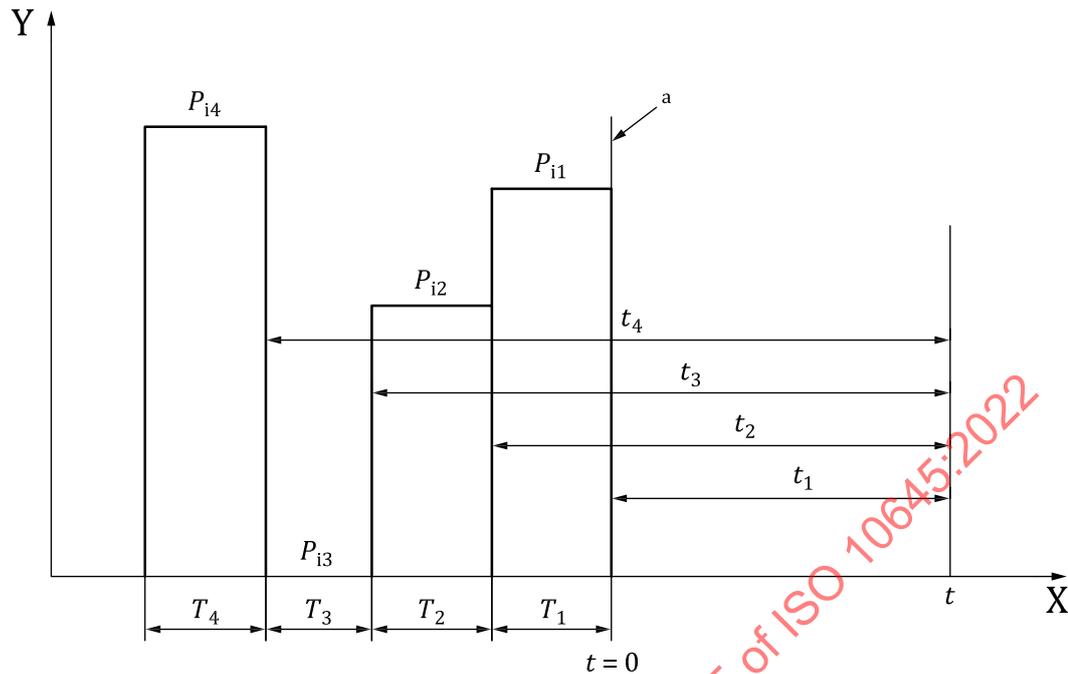
Key

X time

Y power

a Shutdown.

Figure 1 — Power histogram illustration

Thus, for the decay heat power contributions $P_{Si}(t,T)$, the individual times t_k are calculated using Formula (7).

$$t_1 = t$$

$$t_2 = t + T_1$$

$$t_m = t + \sum_{k=1}^{m-1} T_k \tag{7}$$

The relative standard deviation of the decay heat power $\Delta P_{Si}/P_{Si}$ of the fission products is calculated from the standard deviation $\Delta F_i(t_k, T_k)$ and the relative standard deviation $\Delta Q_i/Q_i$.

The contribution of the fissile nuclide i is calculated using Formula (8).

$$\left(\frac{\Delta P_{Si}}{P_{Si}} \right)^2 = \left(\frac{\Delta Q_i}{Q_i} \right)^2 + \left[\frac{\sum_{k=1}^{m} \frac{P_{ik}}{Q_i} \Delta F_i(t_k, T_k)}{P_{Si}} \right]^{2} \tag{8}$$

The values of Q_i and ΔQ_i are given in Table 6.

For decay time $t_k \geq 1$ s, the standard deviation $\Delta F_i(t_k, T_k)$ is calculated using the Formula (9).

$$\Delta F_i\left(t_k, T_k\right) = \int_0^{T_k} \Delta f_i\left(T_k - T' + t_k\right) \mathrm{d}T' \tag{9}$$

A representation analogous to Formula (4) is adopted to calculate $\Delta f_i(t)$ using the following Formula (10).

NOTE   The values of coefficients λ_{ij} and β_{ij}, are given in Tables 2, 3, 4, and 5.

$$\Delta f_i(t) = \sum_{j=1}^{23} \beta_{ij} e^{-\lambda_{ij} t} \tag{10}$$

Hence, the following Formula (11) is thus obtained.

$$\Delta F_i\left(t_k, T_k\right) = \sum_{j=1}^{23} \left[\frac{\beta_{ij}}{\lambda_{ij}} \left(1 - e^{-\lambda_{ij} T_k}\right) e^{-\lambda_{ij} t_k} \right] \tag{11}$$

For decay times $t_k < 1$ s, the standard deviation $\Delta F_i(t_k, T_k)$ is calculated using the Formula (12).

$$\Delta F_i\left(t_k, T_k\right) = \frac{F_i\left(t_k, T_k\right)}{F_i\left(t_k = 1\,s, T_k\right)} \Delta F_i\left(t_k = 1\,s, T_k\right) \tag{12}$$

The standard deviation ΔP_S of the decay heat power of all fission products is calculated using the Formula (13).

$$\left| \Delta P_S \right| = \sum_{i=1}^{4} \left| \Delta P_{Si} \right| \tag{13}$$

5.4   Contribution of actinides

5.4.1   Contribution of ^{239}U and ^{239}Np

The decay heat power $P_B(t, T)$ from ^{239}U and ^{239}Np is calculated using the Formula (14).

$$P_B(t, T) = \sum_{k=1}^{m} \frac{P_k}{Q} \left[F_U\left(t_k, T_K\right) + F_{Np}\left(t_k, T_k\right) \right] \tag{14}$$

P_k/Q is the total fission rate in time interval k and is substituted in Formula (14) as shown in Formula (15).

$$\frac{P_k}{Q} = \sum_{i=1}^{4} \frac{P_{ik}}{Q_i} \tag{15}$$

For the summation in Formula (14), only the last 20 days of the power histogram need to be considered. The terms $F_U(t_k, T_k)$ and $F_{Np}(t_k, T_k)$ in Formula (14) are calculated using Formulae (16) and (17) respectively.

$$F_U\left(t_k, T_k\right) = E_U R \left(1 - e^{-\lambda_U T_k}\right) e^{-\lambda_U t_k} \tag{16}$$

$$F_{Np}\left(t_k, T_k\right) = E_{Np} R \left[\frac{\lambda_U}{\lambda_U - \lambda_{Np}} \left(1 - e^{-\lambda_{Np} T_k}\right) e^{-\lambda_{Np} t_k} - \frac{\lambda_{Np}}{\lambda_U - \lambda_{Np}} \left(1 - e^{-\lambda_U T_k}\right) e^{-\lambda_U t_k} \right] \tag{17}$$

where

E_U (= 0,460 MeV) is the mean decay energy of ^{239}U;

E_{Np} (= 0,405 MeV) is the mean decay energy of ^{239}Np;

λ_U (= 4,926 × 10^{-4} s^{-1}) is the decay constant of ^{239}U;

λ_{Np} (= 3,405 × 10^{-6} s^{-1}) is the decay constant of ^{239}Np;

R is the ratio of the neutron capture rate in ^{238}U to the total fission rate at the end of the operating time.

If the user does not have values for R, the following approximation, as shown in Formula (18), may be used.

$$R = 0{,}974 a_0{}^{-0{,}504} + B_f \left(0{,}008\ 83 - a_0 \times 0{,}000\ 726\right) \tag{18}$$

where

a_0 is the initial enrichment of ^{235}U (percentage by mass);

B_f is the final burnup of the fuel, in megawatt days per kilogram of initial uranium.

Formula (18) was developed for a light water reactor (LWR) spectrum and applies to initial enrichments between 1,9 % and 5,0 %. It yields conservatively high results.

5.4.2   Contribution of other actinides

The contribution $P_A(t,T)$ of the other actinides resulting from the neutron capture (excluding ^{239}U and ^{239}Np) is to be stated by the user.

Formula (19)

$$P_A(t,T) = A(t) P_S(t,T) \tag{19}$$

yields conservatively high results, when using the factors $A(t)$ from Table 7, provided the following conditions are fulfilled:

— initial enrichment, expressed as percentage by mass, 1,9 % ≤ a_0 ≤ 5,0 %;

— burnup, in megawatts days per kilogram of initial uranium, B_f ≤ 12,5 a_0;

— power density, in kilowatts per kilogram of uranium, S ≥ 5,0 a_0.

5.5   Contribution by neutron capture in fission products

5.5.1   Contribution of ^{134}Cs

The ^{134}Cs produced by neutron capture on the fission product ^{133}Cs can have a significant contribution to the decay heat power, particularly for decay times in the region of 10^8 s, and is therefore treated explicitly.

The following Formula (20) applies

$$P_{Cs}(t,T) = \frac{P}{Q} F_{Cs}(t,T)$$ (20)

Where Formula (21) defines the value of P/Q

$$\frac{P}{Q} = \sum_{i=1}^{4} \frac{P_i}{Q_i}$$ (21)

and Formula (22) defines $F_{Cs}(t,T)$.

$$F_{Cs}(t,T) = \lambda_4 E_{Cs} y \left[\frac{1 - e^{-(\lambda_4 + \sigma_4 \phi)T}}{\lambda_4 + \sigma_4 \phi} + \frac{e^{-\sigma_3 \phi T} - e^{-(\lambda_4 + \sigma_4 \phi)T}}{\sigma_3 \phi - (\lambda_4 + \sigma_4 \phi)} \right] e^{-\lambda_4 t}$$ (22)

where

y (= 0,068 3 atoms fission^{-1}) is the mean ^{133}Cs cumulative yield per fission;

E_{Cs} (= 1,719 MeV) is the mean decay energy of ^{134}Cs;

λ_4 (= 1,064 × 10^{-8} s^{-1}) is the decay constant of ^{134}Cs;

ϕ is the total neutron flux in cm^{-2} s^{-1};

σ_3 (= 11,3 × 10^{-24} cm^2) is the spectrum-averaged (n,γ) cross-section of ^{133}Cs;

σ_4 (= 10,9 × 10^{-24} cm^2) is the spectrum-averaged (n,γ) cross-section of ^{134}Cs.

The cross section constants σ_3 and σ_4 were determined for a typical pressurized water reactor (PWR) spectrum. When applied to a boiling water reactor (BWR) they yield conservatively high results.

For a power histogram, an effective irradiation time T_{eff}, an effective neutron flux ϕ_{eff} and a mean fission rate P/Q are to be used in formulae (20) and (22).

Formula (23) defines T_{eff}

$$T_{eff} = \sum_{k=1}^{m} T_k \, (\text{for all } k \text{ with } \Phi_k \neq 0)$$ (23)

And Formula (24) defines the effective neutron flux ϕ_{eff}

$$\phi_{eff} = \frac{1}{T_{eff}} \sum_{k=1}^{m} \phi_k T_k$$ (24)

And Formula (25) defines the values of mean fission rate P/Q.

$$\frac{P}{Q} = \frac{1}{T_{eff}} \sum_{k=1}^{m} \sum_{i=1}^{4} \frac{P_{ik}}{Q_i} T_k$$ (25)

If no value for neutron flux is available, the following approximation, see Formula (26) can be used.

$$\phi_k = \frac{S_k}{a_{eff}} \times 2,58 \times 10^{13} \left(\text{cm}^{-2}\text{s}^{-1} \right)$$ (26)

where

S_k is the power density, in kilowatts per kilogram of uranium in the fuel;

a_{eff} is the effective enrichment of fissile material which is calculated from the initial enrichment a_0, expressed as a percentage by mass.

$$a_{\text{eff}} = \frac{a_0}{2} + 1{,}0 \tag{27}$$

For enrichments and burnups typical of LWRs, ϕ_k in Formula (26) yields values of $P_{\text{Cs}}(t,T)$ which exceed the exact values by up to 5 %. For shorter irradiation times (<25 MWd/kg) the approximate solution overestimates $P_{\text{Cs}}(t,T)$ by up to 15 %.

5.5.2   Contribution of other fission products

The contribution $P_{\text{E}}(t,T)$ made to the decay heat power by neutron capture in fission products (except in ^{133}Cs) is to be stated by the user.

The Formula (28)

$$P_{\text{E}}(t,T) = H(t)\, P_S(t,T) \tag{28}$$

yields conservatively high results, when using the factors $H(t)$ from Table 8, provided that the following boundary conditions are fulfilled:

—   initial enrichment, expressed as a percentage by mass, $1{,}9\ \% \leq a_0 \leq 5{,}0\ \%$;

—   burnup, in megawatts days per kilogram of uranium, $B_f \leq 12{,}5\ a_0$;

—   power density, in kilowatts per kilogram of uranium, $S \geq 5\ a_0$.

5.6   Total decay heat power

The total decay heat power is calculated using the Formula (29).

$$P_{\text{N}}(t,T) = P_S(t,T) + P_B(t,T) + P_A(t,T) + P_{Cs}(t,T) + P_{\text{E}}(t,T) \tag{29}$$

The error bandwidth ΔP_{N} shall be determined from standard deviation ΔP_S, [see Formula (13)] associated with the fission product contribution and the uncertainty of the relative thermal power during operation ($\Delta P/P$) using the Formula (30).

$$\Delta P_{\text{N}}(t,T) = n\sqrt{\left[\Delta P_S(t,T)\right]^2 + \left[P_{\text{N}}(t,T)\frac{\Delta P}{P}\right]^2} \tag{30}$$

where n is the multiple of the standard deviation associated with the chosen confidence level.

The other contributions to the decay heat power P_{B}, P_{A}, P_{Cs}, and P_{E} shall be determined conservatively and therefore do not enter into the calculation of the error bandwidth. Using the approximate methods of this document for these contributions results in conservative estimates of the total decay heat power. Alternative methods, such as those based on comparisons of code predictions and isotopic measurements for the main nuclides contributing to each of these decay heat terms, shall be specified, and justified by the user.

Table 2 — Coefficients for thermal fission of ^{235}U

j	α $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$a	β $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$a	λ (s^{-1})a
1	5,280 0E-04	1,227 6E-04	2,721 6E+00
2	6,858 8E-01	2,986 2E-01	1,025 6E+00
3	4,075 2E-01	1,490 1E-02	3,141 9E-01
4	2,193 7E-01	9,636 9E-03	1,178 8E-01
5	5,770 1E-02	1,068 0E-03	3,436 5E-02
6	2,253 0E-02	4,070 5E-04	1,176 2E-02
7	3,339 2E-03	7,872 6E-05	3,606 5E-03
8	9,366 7E-04	1,679 5E-05	1,396 3E-03
9	8,089 9E-04	1,447 4E-05	6,260 8E-04
10	1,957 2E-04	4,372 4E-06	1,892 4E-04
11	3,260 9E-05	5,117 8E-07	5,507 4E-05
12	7,582 7E-06	2,099 7E-08	2,097 1E-05
13	2,518 9E-06	7,925 8E-08	9,994 0E-06
14	4,983 6E-07	9,330 1E-09	2,540 1E-06
15	1,852 3E-07	3,785 5E-09	6,633 2E-07
16	2,659 2E-08	5,400 4E-10	1,228 1E-07
17	2,235 6E-09	4,535 7E-11	2,716 3E-08
18	8,9582E-12	5,5496E-14	3,2955E-09
19	8,5968E-11	1,8015E-12	7,4225E-10
20	2,1072E-14	4,9806E-15	2,4681E-10
21	7,1219E-16	-7,4576E-17	1,5596E-13
22	8,1126E-17	2,5589E-15	2,2573E-14
23	9,4678E-17	-2,4567E-15	2,0503E-14

a   See Formulae (4), (5), (6), (10), (11) and (12).

Table 3 — Coefficients for fast fission of ^{238}U

j	α $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$a	β $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$a	λ (s^{-1})a
1	3,936 8E-01	1,592 6E-01	4,342 7E+00
2	7,458 8E-01	2,581 2E-02	1,711 4E+00
3	1,216 9E+00	3,852 6E-01	6,057 2E-01
4	5,282 0E-01	1,150 1E-01	1,942 9E-01
5	1,480 5E-01	3,401 0E-03	6,978 8E-02
6	4,598 0E-02	3,448 2E-03	1,880 9E-02
7	1,040 6E-02	6,156 7E-04	6,126 5E-03
8	1,699 1E-03	9,581 0E-05	1,379 9E-03
9	6,910 2E-04	2,993 1E-05	5,279 9E-04
10	1,473 6E-04	9,354 4E-06	1,614 5E-04
11	2,404 9E-05	1,714 6E-06	4,841 9E-05

a   See Formulae (4), (5), (6), (10), (11) and (12).

Table 3 *(continued)*

j	α $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$[a]	β $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$[a]	λ (s^{-1})[a]
12	6,928 8E-06	3,529 7E-07	1,564 4E-05
13	6,492 7E-07	2,336 6E-08	5,361 0E-06
14	4,355 6E-07	1,656 0E-08	2,168 9E-06
15	1,602 0E-07	5,627 7E-09	6,334 3E-07
16	2,308 9E-08	7,996 0E-10	1,287 9E-07
17	2,548 1E-09	1,151 4E-10	2,560 4E-08
18	3,507 1E-11	4,697 6E-12	9,154 4E-09
19	6,339 9E-11	2,877 8E-12	7,394 0E-10
20	4,159 9E-14	1,743 8E-15	2,473 1E-10
21	5,329 5E-16	4,239 4E-17	1,959 4E-13
22	1,669 5E-18	-1,678 9E-14	6,430 3E-14
23	4,105 8E-16	1,678 5E-14	6,422 9E-14

[a] See Formulae (4), (5), (6), (10), (11) and (12).

Table 4 — Coefficients for thermal fission of ^{239}Pu

j	α $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$[a]	β $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$[a]	λ (s^{-1})[a]
1	1,654 0E+00	6,230 8E-01	8,924 6E+00
2	3,692 8E-01	2,495 2E-01	6,900 5E-01
3	2,400 6E-01	-1,059 3E-02	2,361 8E-01
4	1,026 9E-01	1,397 4E-02	1,011 8E-01
5	3,491 6E-02	3,836 6E-04	3,719 3E-02
6	2,296 1E-02	1,089 1E-03	1,431 9E-02
7	3,907 0E-03	3,920 7E-05	4,509 4E-03
8	1,308 0E-03	7,475 1E-05	1,321 1E-03
9	7,026 5E-04	1,627 9E-05	5,348 1E-04
10	1,429 7E-04	1,739 7E-06	1,729 7E-04
11	1,764 2E-05	1.473 0E-06	4,891 8E-05
12	7,364 6E-06	2,032 3E-07	2,015 5E-05
13	1,772 0E-06	1,322 8E-07	8,368 7E-06
14	5,494 5E-07	2,839 0E-08	2,362 0E-06
15	1,673 6E-07	8,511 5E-09	6,459 4E-07
16	2,116 0E-08	1,058 3E-09	1,282 2E-07
17	2,938 8E-09	1,472 1E-10	2,516 6E-08
18	1,365 9E-10	7,590 6E-12	1,317 6E-08
19	5,745 0E-11	2,874 2E-12	7,356 8E-10
20	3,842 2E-14	5,499 8E-15	2,466 3E-10
21	1,803 0E-16	-1,870 6E-16	3,349 0E-13
22	1,834 2E-15	1,774 7E-16	1,876 1E-13

[a] See Formulae (4), (5), (6), (10), (11) and (12).

Table 4 *(continued)*

j	α $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$ a	β $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$ a	λ (s^{-1}) a
23	1,988 4E-16	1,409 1E-16	3,154 4E-14
a See Formulae (4), (5), (6), (10), (11) and (12).			

Table 5 — Coefficients for thermal fission of ^{241}Pu

j	α $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$ a	β $\left(\dfrac{\text{MeV/s}}{\text{fission}}\right)$ a	λ (s^{-1}) a
1	3,093 4E-01	6,527 5E-02	2,904 9E+00
2	5,443 4E-01	2,897 6E-01	6,491 1E-01
3	4,078 2E-01	4,894 3E-05	2,556 9E-01
4	1,582 8E-01	1,065 5E-02	8,712 3E-02
5	4,157 7E-02	8,211 6E-04	2,506 8E-02
6	1,481 8E-02	9,075 6E-04	1,332 3E-02
7	5,817 6E-03	1,182 2E-04	6,377 2E-03
8	1,948 2E-03	7,652 5E-05	2,022 1E-03
9	9,519 6E-04	3,433 6E-05	6,293 3E-04
10	1,820 8E-04	4,489 0E-06	1,746 2E-04
11	1,531 0E-05	2,307 2E-06	4,017 2E-05
12	4,503 9E-06	5,415 3E-07	1,528 9E-05
13	9,827 7E-07	1,172 5E-07	7,611 3E-06
14	5,183 2E-07	4,950 1E-08	2,508 3E-06
15	2,301 8E-08	3,098 9E-09	1,131 2E-06
16	1,581 7E-07	1,578 8E-08	6.,987E-07
17	1,807 4E-08	1,814 8E-09	1,314 9E-07
18	3,692 2E-09	3,679 4E-10	2,423 7E-08
19	5,384 3E-11	5,908 6E-12	9,643 3E-09
20	5,300 3E-11	5,311 4E-12	7,346 7E-10
21	4,835 8E-14	1,393 5E-14	2,482 7E-10
22	9,851 6E-16	1,283 4E-16	1,687 3E-13
23	1,307 6E-16	6,058 0E-18	8,363 9E-15
a See Formulae (4), (5), (6), (10), (11) and (12).			

Table 6 — Total effective thermal energy Q released as a result of one nuclear fission event of each fissile nuclide, and the corresponding standard deviation ΔQ (values in units of MeV/ fission)

i	Fissile nuclide	Q_{eff} a	Q_c b	Q_{total}	ΔQ
1	^{235}U	193,5	8,7	202,2	±0,5
2	^{238}U	194,6	10,9	205,5	±1,0
a Q_{eff} is the effective thermal energy resulting from one nuclear fission event.					
b Q_c is the effective thermal energy released from neutron capture not resulting in nuclear fission, based on a mean energy per capture of 6,1 MeV, which is characteristic of LWRs. The mean energy per capture applicable to each distinct case may be inserted by the user as appropriate.					

Table 6 *(continued)*

i	**Fissile nuclide**	Q_{eff} [a]	Q_c [b]	Q_{total}	ΔQ
3	^{239}Pu	199,7	11,5	211,2	±0,7
4	^{241}Pu	201,8	11,9	213,7	±0,7

[a] Q_{eff} is the effective thermal energy resulting from one nuclear fission event.

[b] Q_c is the effective thermal energy released from neutron capture not resulting in nuclear fission, based on a mean energy per capture of 6,1 MeV, which is characteristic of LWRs. The mean energy per capture applicable to each distinct case may be inserted by the user as appropriate.

Table 7 — Factor $A(t)$ for calculating the actinide contribution (excluding ^{239}U and ^{239}Np) to the decay heat power according to Formula (19)

$t(s)$[a]	$A(t)$	$t(s)$[a]	$A(t)$
0	0,008	$4,0 \times 10^4$	0,071
1	0,009	$6,0 \times 10^4$	0,075
1,5	0,009	$8,0 \times 10^4$	0,077
2	0,010	$1,0 \times 10^5$	0,079
3	0,010	$1,5 \times 10^5$	0,081
4	0,011	$2,0 \times 10^5$	0,083
6	0,011	$3,0 \times 10^5$	0,085
8	0,012	$4,0 \times 10^5$	0,086
10	0,012	$6,0 \times 10^5$	0,089
15	0,013	$8,0 \times 10^5$	0,092
20	0,013	$1,0 \times 10^6$	0,095
30	0,014	$1,5 \times 10^6$	0,104
40	0,015	$2,0 \times 10^6$	0,112
60	0,016	$3,0 \times 10^6$	0,127
80	0,017	$4,0 \times 10^6$	0,140
100	0,018	$6,0 \times 10^6$	0,156
150	0,020	$8,0 \times 10^6$	0,171
200	0,021	$1,0 \times 10^7$	0,181
300	0,023	$1,5 \times 10^7$	0,196
400	0,024	$2,0 \times 10^7$	0,203
600	0,026	$3,0 \times 10^7$	0,206
800	0,028	$4,0 \times 10^7$	0,207
$1,0 \times 10^3$	0,029	$6,0 \times 10^7$	0,222
$1,5 \times 10^3$	0,033	$8,0 \times 10^7$	0,257
$2,0 \times 10^3$	0,035	$1,0 \times 10^8$	0,303
$3,0 \times 10^3$	0,040	$1,5 \times 10^8$	0,408
$4,0 \times 10^3$	0,043	$2,0 \times 10^8$	0,470
$6,0 \times 10^3$	0,049	$3,0 \times 10^8$	0.522
$8,0 \times 10^3$	0,053	$4,0 \times 10^8$	0,552
$1,0 \times 10^4$	0,056	$6,0 \times 10^8$	0,608
$1,5 \times 10^4$	0,061	$8,0 \times 10^8$	0,668
$2,0 \times 10^4$	0,064	$1,0 \times 10^9$	0,736
$3,0 \times 10^4$	0,068	—	—
[a] Intermediate values are to be calculated using linear interpolation.			

Table 8 — Factor *H*(*t*) for calculating the contribution by neutron capture (excluding ^{134}Cs) to the decay heat power according to Formula (28)

$t(s)$[a]	$H(t)$	$t(s)$[a]	$H(t)$
0	0,015	$4,0 \times 10^4$	0,055
1	0,016	$6,0 \times 10^4$	0,063
1,5	0,016	$8,0 \times 10^4$	0,068
2	0,016	$1,0 \times 10^5$	0,071
3	0,017	$1,5 \times 10^5$	0,075
4	0,016	$2,0 \times 10^5$	0,077
6	0,017	$3,0 \times 10^5$	0,076
8	0,017	$4,0 \times 10^5$	0,075
10	0,018	$6,0 \times 10^5$	0,071
15	0,017	$8,0 \times 10^5$	0,068
20	0,017	$1,0 \times 10^6$	0,066
30	0,017	$1,5 \times 10^6$	0,059
40	0,016	$2,0 \times 10^6$	0,052
60	0,015	$3,0 \times 10^6$	0,040
80	0,015	$4,0 \times 10^6$	0,031
100	0,015	$6,0 \times 10^6$	0,020
150	0,015	$8,0 \times 10^6$	0,015
200	0,015	$1,0 \times 10^7$	0,012
300	0,016	$1,5 \times 10^7$	0,010
400	0,016	$2,0 \times 10^7$	0,009
600	0,018	$3,0 \times 10^7$	0,11
800	0,019	$4,0 \times 10^7$	0,012
$1,0 \times 10^3$	0,019	$6,0 \times 10^7$	0,015
$1,5 \times 10^3$	0,021	$8,0 \times 10^7$	0,019
$2,0 \times 10^3$	0,023	$1,0 \times 10^8$	0,024
$3,0 \times 10^3$	0,025	$1,5 \times 10^8$	0,033
$4,0 \times 10^3$	0,028	$2,0 \times 10^8$	0,038
$6,0 \times 10^3$	0,031	$3,0 \times 10^8$	0,037
$8,0 \times 10^3$	0,034	$4,0 \times 10^8$	0,033
$1,0 \times 10^4$	0,036	$6,0 \times 10^8$	0,025
$1,5 \times 10^4$	0,040	$8,0 \times 10^8$	0,016
$2,0 \times 10^4$	0,044	$1,0 \times 10^9$	0,011
$3,0 \times 10^4$	0,050	—	—
[a] Intermediate values are to be calculated using linear interpolation.			

Annex A
(informative)

Example of a calculation

A.1 Calculation description

The following example for a pressurized water reactor (PWR) fuel element illustrates the procedure as defined in this document. For the irradiation history, the simplified power histogram in Figure A.1 is used.

For time intervals T_1, T_3 and T_5, the same fuel operating powers P have been assumed. In the time intervals T_2 and T_4, no power is generated. The other input data are as follows:

— Initial enrichment of the fuel: $a_0 = 3,2\ \%$

— Power density in the fuel: $S = 34,3$ kW per kg of uranium

— Uncertainty of fuel element power: $\Delta P = 0$

— Multiple of the standard deviation: $n = 1$

According to Formula (29) the total decay heat power is

$$P_N = P_S + P_B + P_A + P_{Cs} + P_E$$

A.2 Calculation of P_S

The contribution P_S of the individual fission isotopes to the decay heat power is calculated by means of Formula (6), with the numerical values in Table A.1 being substituted for the P_{ik} and T_k of the individual time intervals. Values for P_{ik} are not defined by this document and are to be obtained from literature sources[3][4] or calculated using validated computer codes. The power fractions are related to the fission fractions for the fissile isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu. The values below are intended only for the purposes of this example calculation. These values are primarily dependent on the enrichment of the fuel, the burnup, and the reactor type.

Table A.1 — Power fraction P_{ik}/P used in the example calculation

$P_{11}/P = 0,80$	$P_{21}/P = 0,06$	$P_{31}/P = 0,13$	$P_{41}/P = 0,01$
$P_{12}/P = 0,00$	$P_{22}/P = 0,00$	$P_{32}/P = 0,00$	$P_{42}/P = 0,00$
$P_{13}/P = 0,60$	$P_{23}/P = 0,07$	$P_{33}/P = 0,29$	$P_{43}/P = 0,04$
$P_{14}/P = 0,00$	$P_{24}/P = 0,00$	$P_{34}/P = 0,00$	$P_{44}/P = 0,00$
$P_{15}/P = 0,40$	$P_{25}/P = 0,08$	$P_{35}/P = 0,42$	$P_{45}/P = 0,10$