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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 k^{th} time interval T_k	[a]
P_{ik}	Contribution of the fissile nuclide i to the thermal power of the fuel during the k^{th} 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).

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

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).

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

where

P_{ik} is the total thermal power released by the fuel during fission;

Q_i is the total thermal energy released by a single fission;

P_{ik}/Q_i 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).

$$F_i(t_k,T_k)=\int_{0}^{T_k}f_i(T_k-T'+t_k)\,\mathrm{d}T' \tag{3}$$

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

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

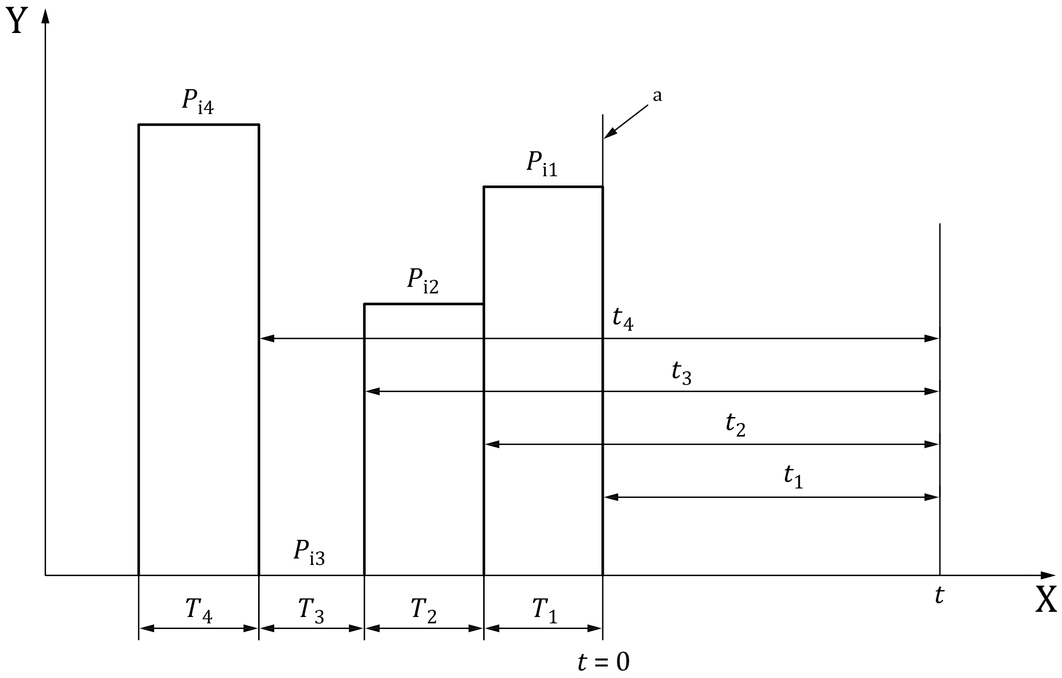
The following Formula (5) is thus obtained.

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

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

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

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).

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

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