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Nuclear energy — Light water reactors — Calculation of the decay heat power in nuclear fuels

Énergie nucléaire — Réacteurs à eau légère — Calcul de la puissance résiduelle des combustibles nucléaires

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Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 10645 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Sub-Committee SC 3, *Power reactor technology*.

Annex A forms an integral part of this International Standard.

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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 following the shutdown of a nuclear reactor. It is an important physical quantity for the design of systems in which the decay heat power has to be taken into consideration as a heat source.

This International Standard gives the local generation of decay heat power as a function of the thermal fuel power during operation. 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 decay heat power to be calculated with an accuracy comparable to that of summation codes but without the need for complicated calculations.

For calculating the decay heat power or its individual components, the user can employ methods and data bases of his own, provided that their validity is established. For the fission product contribution, this requires comparison with this International Standard.

The power generated by delayed neutrons and activated structural material is not considered in this International Standard.

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Nuclear energy — Light water reactors — Calculation of the decay heat power in nuclear fuels

1 Scope

This International Standard 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 International Standard applies to light water reactors (pressurized water and boiling water reactors) loaded with a nuclear fuel mixture consisting of ^{235}U and ^{238}U. Its application to recycled nuclear fuel is not permissible.

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

2 Definitions

For the purposes of this International Standard, the following definitions apply.

2.1 decay heat power of nuclear fuels: The thermal power produced by radioactive decay of fission and activation products of the nuclear fuel, following shutdown of a nuclear fission reactor.

2.2 operating time: The entire period from the first charging of the reactor with fuel until the final shutdown considered.

2.3 decay time: The time elapsing after the operating time.

2.4 power histogram: This approximates the true variation of power with time, subdivided into intervals of constant power output and fuel composition.

3 Symbols and subscripts

3.1 Symbols

Symbol	Quantity	Unit
$A(t)$	Factor to be applied to the decay heat power of the fission products P_S for calculating the contribution P_A of the actinides (excluding ^{239}U and ^{239}Np)	—
$f_i(t)$	Decay heat power of the fission products at time t after a single nuclear fission of the fissile nuclide i	$\frac{\text{MeV/s}}{\text{by fission}}$
$\Delta f_i(t)$	Standard deviation of $f_i(t)$	$\frac{\text{MeV/s}}{\text{by fission}}$
$F_i(t_k, T_k)$	Decay heat power of the fission products of the fissile nuclide i at time t_k after the irradiation time interval T_k referred to one fission per second	$\frac{\text{MeV/s}}{\text{by fission/s}}$
$\Delta F_i(t_k, T_k)$	Standard deviation of $F_i(t_k, T_k)$	$\frac{\text{MeV/s}}{\text{by fission/s}}$
$H(t)$	Factor to be applied to the decay heat power of the fission products P_S for calculating the contribution P_E from neutron capture in fission products (excluding capture in ^{133}Cs)	—

Symbol	Quantity	Unit
P_k	Total thermal power of the fuel during the k^{th} time interval T_k	1)
P_{ik}	Contribution of the fissile nuclide i to the thermal power of the fuel during the k^{th} time interval T_k	2)
$P_N(t,T)$	Total decay heat power at time t after the end of operating time T	2)
$P_S(t,T)$	Summed decay heat power on the basis of fission product decays	2)
$\Delta P_S(t,T)$	Standard deviation of $P_S(t,T)$	2)
$P_{Si}(t,T)$	Contribution of the fissile nuclide i to the decay heat power $P_S(t,T)$	2)
$\Delta P_{Si}(t,T)$	Standard deviation of $P_{Si}(t,T)$	2)
$P_E(t,T)$	Contribution to the decay heat power through neutron capture in fission products (excluding capture in ^{133}Cs)	2)
$P_B(t,T)$	Contribution of actinides ^{239}U and ^{239}Np to the decay heat power	2)
$P_A(t,T)$	Contribution of actinides (excluding ^{239}U and ^{239}Np) to the decay heat power	2)
$P_{Cs}(t,T)$	Contribution of ^{134}Cs to the decay heat power	2)
Q_i	Total thermal energy released from one nuclear fission of the fissile nuclide i	$\frac{\text{MeV}}{\text{by fission}}$
ΔQ_i	Standard deviation of the thermal energy released from one nuclear fission of the fissile nuclide i	$\frac{\text{MeV}}{\text{by fission}}$
t	Decay time (see 2.3 and figure 1)	s
t_k	Time from the end of the k^{th} time interval T_k in the power histogram (see figure 1)	s
T	Operating time (see 2.2 and figure 1)	s
T_k	Duration of the k^{th} time interval 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 the fission products as the summation of 24 exponential functions	$\frac{\text{MeV/s}}{\text{by fission}}$
β_{ij}	Coefficient representing the standard deviation3) of the decay heat power of the fission products as the summation of 24 exponential functions	$\frac{\text{MeV/s}}{\text{by fission}}$
λ_{ij}	Exponent used for representing the decay heat power of the fission products and its standard deviations as the summation of 24 exponential functions	s^{-1}

1) Any power unit can be used.
2) Same unit as P_k.
3) For ^{241}Pu a value of 5 % has been assumed.

3.2 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 intervals T_k in the power histogram

4 Calculation of decay heat power

4.1 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 decay times t between 0 and 10^9 s.

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

4.2 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 subdividing the operating time into intervals of constant power and constant fissile nuclides (approximated composition, see figures 1 and A.1). It has to be ensured that the systematic error introduced by this approximation remains small compared with the statistical error of the calculated decay heat power. This can be achieved 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. 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.

It is important to ensure that, in each time interval of the histogram, the time integral of the total power and the power from each fissile nuclide agrees with the corresponding value of the actual power histogram.

4.3 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 the formula

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

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 follows

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

where

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

Q_i is the total thermal energy released by a single fission (see table 1);

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 follows:

$$F_i(t_k,T_k) = \int_0^{T_k} f_i(T_k - T' + t_k)\,\mathrm{d}T' \qquad \ldots (3)$$

$f_i(t)$ is calculated as follows by using the coefficients α_{ij}, λ_{ij} given in table 2.

$$f_i(t) = \sum_{j=1}^{24} \alpha_{ij} \mathrm{e}^{-\lambda_{ij} t} \qquad \ldots (4)$$

The following equation is thus obtained.

$$F_i(t_k,T_k) = \sum_{j=1}^{24} \frac{\alpha_{ij}}{\lambda_{ij}} \left(1 - \mathrm{e}^{-\lambda_{ij} T_k}\right) \mathrm{e}^{-\lambda_{ij} t_k} \qquad \ldots (5)$$

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

$$P_S(t,T) = \sum_{i=1}^{4} \sum_{k=1}^{m} \left\{ \frac{P_{ik}}{Q_i} \sum_{j=1}^{24} \left[\frac{\alpha_{ij}}{\lambda_{ij}} \left(1 - \mathrm{e}^{-\lambda_{ij} T_k}\right) \mathrm{e}^{-\lambda_{ij} t_k} \right] \right\} \qquad \ldots (6)$$

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

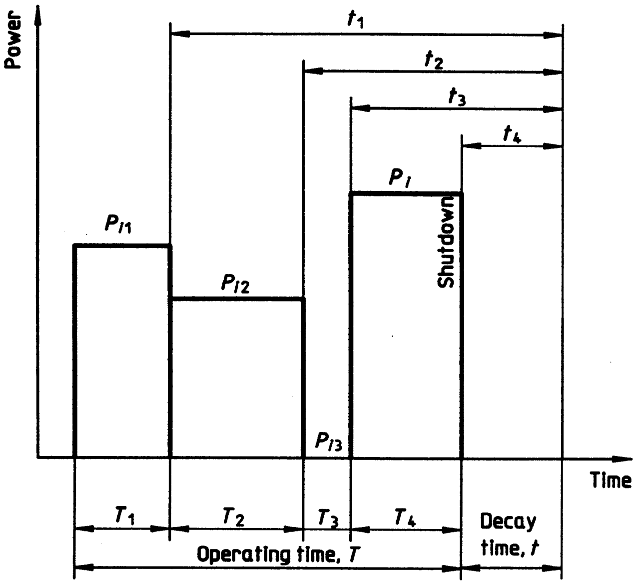

Figure 1 — Power histogram

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

$$t_m = t$$

$$t_{m-1} = t + T_m$$

$$t_1 = t + \sum_{k=2}^{m} T_k \qquad \ldots (7)$$

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 the formula

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

The values of Q_i and ΔQ_i are given in table 1.

For decay time $t_k \geqslant 1$, the standard deviation $\Delta F_i(t_k,T_k)$ is calculated using the formula

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

A representation analogous to formula (4) is adopted to calculate $\Delta f_i(t)$ using the following formula. (The values of coefficients λ_{ij} and β_{ij} are given in table 2.)

$$\Delta f_i(t) = \sum_{j=1}^{24} \beta_{ij} \mathrm{e}^{-\lambda_{ij}t} \qquad \ldots (10)$$

hence

$$\Delta F_i(t_k,T_k) = \sum_{j=1}^{24} \frac{\beta_{ij}}{\lambda_{ij}} (1 - \mathrm{e}^{-\lambda_{ij}T_k})\mathrm{e}^{-\lambda_{ij}t_k} \qquad \ldots (11)$$

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

$$\Delta F_i(t_k,T_k) = \frac{F_i(t_k,T_k)}{F_i(t_k = 1\ \mathrm{s},T_k)} \Delta F_i(t_k = 1\ \mathrm{s},T_k) \qquad \ldots (12)$$

The standard deviation ΔP_S of the decay heat power of all fission products is calculated using the formula

$$|\,\Delta P_S\,| = \sum_{i=1}^{4} |\,\Delta P_{Si}\,| \qquad \ldots (13)$$

4.4 Contribution of actinides

4.4.1 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

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

P_k/Q is the total fission rate in time interval k and is substituted in formula (14) as follows:

$$\frac{P_k}{Q} = \sum_{i=1}^{4} \frac{P_{ik}}{Q_i} \qquad \ldots (15)$$

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.

$$F_U(t_k,T_k) = E_U R(1 - \mathrm{e}^{-\lambda_U T_k})\mathrm{e}^{-\lambda_U t_k} \qquad \ldots (16)$$

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

where

E_U (= 0,474 MeV) is the mean decay energy of ^{239}U;

E_{Np} (= 0,419 MeV) is the mean decay energy of ^{239}Np;

λ_U ($= 4,91 \times 10^{-4}\ s^{-1}$) is the decay constant of ^{239}U;

λ_{Np} ($= 3,41 \times 10^{-6}\ s^{-1}$) 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 any values for R, the following approximation may be used:

$$R = 1{,}18e^{-0{,}141a_0} - 0{,}2 + 6{,}2 \times 10^{-3}BU \qquad \ldots (18)$$

where

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

BU is the burn-up of the fuel, in megawatts day per kilogram of uranium.

Formula (18) was developed for a typical light water reactor (LWR) spectrum and applies to initial enrichments between 1,9 % and 4,1 %. It yields conservatively high results.

4.4.2 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.

The formula

$$P_A(t,T) = A(t)P_S(t,T) \qquad \ldots (19)$$

yields conservatively high results, when using the factors $A(t)$ from table 3, provided the following boundary conditions are fulfilled:

— initial enrichment, expressed as percentage by mass, 1,9 % $\leqslant a_0 \leqslant$ 4,1 %;

— burn-up, in megawatts day per kilogram of uranium, BU $\leqslant 12{,}5a_0$;

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

4.5 Contribution by neutron capture in fission products

4.5.1 Contribution of ^{134}Cs

The ^{134}Cs produced by the reaction $^{133}Cs + n$ may 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 applies

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

where

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

and

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

where

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

E_{Cs} (= 1,717 MeV) is the mean decay energy of ^{134}Cs;

λ_4 ($= 1{,}071 \times 10^{-8}\ s^{-1}$) is the decay constant of ^{134}Cs;

Φ is the total neutron flux in $cm^{-2} \cdot s^{-1}$;

σ_3 ($= 10{,}7 \times 10^{-24}\ cm^2$) is the spectrum-averaged (n, γ) cross-section of ^{133}Cs.

σ_4 ($= 16{,}8 \times 10^{-24}\ cm^2$) is the spectrum-averaged (n, γ) cross-section of ^{134}Cs.

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).

These are to be determined as follows:

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

$$\Phi_{\text{eff}} = \frac{1}{T_{\text{eff}}} \sum_{k=1}^{m} \Phi_k T_k \qquad \dots (24)$$

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

If no value for neutron flux is available, the following approximation can be used:

$$\Phi_k = \frac{S_k}{a_{\text{eff}}} \times 2{,}58 \times 10^{13} \ (\text{cm}^{-2} \cdot \text{s}^{-1}) \qquad \dots (26)$$

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.

$$a_{\text{eff}} = \frac{a_0}{2} + 1{,}0 \qquad \dots (27)$$

For enrichments and burn-ups 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 ($\leqslant$ 25 MWd/kg) the approximate solution overestimates $P_{\text{Cs}}(t,T)$ by up to 15 %.

4.5.2 Contribution of remaining capture reactions

The contribution $P_E(t,T)$ 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

$$P_E(t,T) = H(t) P_S(t,T) \qquad \dots (28)$$

yields conservatively high results, when using the factors $H(t)$ from table 4, provided that the following boundary conditions are fulfilled:

— initial enrichment, expressed as a percentage by mass, 1,9 % $\leqslant a_0 \leqslant$ 4,1 %;

— burn-up, in megawatts day per kilogram of uranium, BU $\leqslant 12{,}5 a_0$;

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

4.6 Total decay heat power

The total decay heat power is calculated using the formula

$$P_N(t,T) = P_S(t,T) + P_B(t,T) + P_A(t,T) + P_{\text{Cs}}(t,T) + P_E(t,T) \qquad \dots (29)$$

The associated error bandwidth ΔP_N shall be determined from standard deviation ΔP_S [see formula (13)] and the uncertainty of the thermal power during operation ($\Delta P/P$) using the formula

$$\Delta P_N(t,T) = n \sqrt{[\Delta P_S(t,T)]^2 + \left[P_N(t,T) \times \frac{\Delta P}{P}\right]^2} \qquad \dots (30)$$

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 do not enter into the calculation of the uncertainty bandwidth. Using the approximate methods of this International Standard for these contributions results in reasonably conservative overestimates. If the user does not have values permitting conservative underestimates of the total decay heat power, then $P_N(t,T) = P_S(t,T)$ may be used.

Table 1 — Total effective thermal energy Q_i released as a result of one nuclear fission of fissile nuclide i, and the corresponding standard deviation ΔQ_i

Values in MeV/fission

i	Fissile nuclide	$Q_{\text{eff},i}$ 1)	$Q_{\text{c},i}$ 2)	$Q_i = Q_{\text{eff},i} + Q_{\text{c},i}$	ΔQ_i
1	^{235}U	193,5	8,7	202,2	± 0,5
2	^{238}U	194,6	10,9	205,5	± 1,0
3	^{239}Pu	199,7	11,5	211,2	± 0,7
4	^{241}Pu	201,8	11,9	213,7	± 0,7

1) $Q_{\text{eff},i}$ is the effective thermal energy resulting from one nuclear fission.

2) $Q_{\text{c},i}$ is the effective thermal energy released from neutron captures 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 2 — Coefficients for the thermal fission of ^{235}U, ^{239}Pu, ^{241}Pu and for the fast fission of ^{238}U

Coefficients for the thermal fission of ^{235}U [see formulae (4), (5), (10) and (11)]

j	$\alpha \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\beta \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\lambda\ (s^{-1})$
1	0	$2,964\ 0$	$2,499\ 0$
2	$6,505\ 7 \times 10^{-1}$	$2,573\ 9 \times 10^{-1}$	$2,213\ 8 \times 10$
3	$5,126\ 4 \times 10^{-1}$	$3,894\ 8 \times 10^{-2}$	$5,158\ 7 \times 10^{-1}$
4	$2,438\ 4 \times 10^{-1}$	$9,689\ 7 \times 10^{-3}$	$1,959\ 4 \times 10^{-1}$
5	$1,385\ 0 \times 10^{-1}$	$4,653\ 6 \times 10^{-3}$	$1,031\ 4 \times 10^{-1}$
6	$5,544\ 0 \times 10^{-2}$	$1,135\ 3 \times 10^{-3}$	$3,365\ 6 \times 10^{-2}$
7	$2,222\ 5 \times 10^{-2}$	$3,989\ 3 \times 10^{-4}$	$1,168\ 1 \times 10^{-2}$
8	$3,308\ 8 \times 10^{-3}$	$6,805\ 6 \times 10^{-5}$	$3,587\ 0 \times 10^{-3}$
9	$9,301\ 5 \times 10^{-4}$	$1,706\ 5 \times 10^{-5}$	$1,393\ 0 \times 10^{-3}$
10	$8,094\ 3 \times 10^{-4}$	$1,413\ 9 \times 10^{-5}$	$6,263\ 0 \times 10^{-4}$
11	$1,956\ 7 \times 10^{-4}$	$4,032\ 2 \times 10^{-6}$	$1,890\ 6 \times 10^{-4}$
12	$3,253\ 5 \times 10^{-5}$	$5,046\ 8 \times 10^{-7}$	$5,498\ 8 \times 10^{-5}$
13	$7,559\ 5 \times 10^{-6}$	$3,701\ 7 \times 10^{-8}$	$2,095\ 8 \times 10^{-5}$
14	$2,523\ 2 \times 10^{-6}$	$5,436\ 2 \times 10^{-8}$	$1,001\ 0 \times 10^{-5}$
15	$4,994\ 8 \times 10^{-7}$	$1,074\ 1 \times 10^{-8}$	$2,543\ 8 \times 10^{-6}$
16	$1,853\ 1 \times 10^{-7}$	$3,604\ 2 \times 10^{-9}$	$6,636\ 1 \times 10^{-7}$
17	$2,660\ 8 \times 10^{-8}$	$5,332\ 7 \times 10^{-10}$	$1,229\ 0 \times 10^{-7}$
18	$2,239\ 8 \times 10^{-9}$	$4,483\ 6 \times 10^{-11}$	$2,721\ 3 \times 10^{-8}$
19	$8,164\ 1 \times 10^{-12}$	$1,631\ 4 \times 10^{-13}$	$4,371\ 4 \times 10^{-9}$
20	$8,779\ 7 \times 10^{-11}$	$1,760\ 8 \times 10^{-12}$	$7,578\ 0 \times 10^{-10}$
21	$2,513\ 1 \times 10^{-14}$	$4,985\ 6 \times 10^{-16}$	$2,478\ 6 \times 10^{-10}$
22	$3,217\ 6 \times 10^{-16}$	$6,403\ 3 \times 10^{-18}$	$2,238\ 4 \times 10^{-13}$
23	$4,503\ 8 \times 10^{-17}$	$9,112\ 2 \times 10^{-19}$	$2,460\ 0 \times 10^{-14}$
24	$7,479\ 1 \times 10^{-17}$	$1,498\ 2 \times 10^{-18}$	$1,569\ 9 \times 10^{-14}$

Coefficients for the thermal fission of ^{239}Pu [see formulae (4), (5), (10) and (11)]

j	$\alpha \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\beta \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\lambda\ (s^{-1})$
1	0	$2,319\ 5$	$2,183\ 6$
2	$2,083\ 0 \times 10^{-1}$	$1,126\ 1 \times 10^{-1}$	$1,002\ 0 \times 10$
3	$3,853\ 0 \times 10^{-1}$	$2,106\ 3 \times 10^{-2}$	$6,433\ 0 \times 10^{-1}$
4	$2,213\ 0 \times 10^{-1}$	$1,134\ 1 \times 10^{-2}$	$2,186\ 0 \times 10^{-1}$
5	$9,460\ 0 \times 10^{-2}$	$5,801\ 0 \times 10^{-3}$	$1,004\ 0 \times 10^{-1}$
6	$3,531\ 0 \times 10^{-2}$	$1,353\ 8 \times 10^{-3}$	$3,728\ 0 \times 10^{-2}$
7	$2,292\ 0 \times 10^{-2}$	$8,760\ 8 \times 10^{-4}$	$1,435\ 0 \times 10^{-2}$
8	$3,946\ 0 \times 10^{-3}$	$1,636\ 0 \times 10^{-4}$	$4,549\ 0 \times 10^{-3}$
9	$1,317\ 0 \times 10^{-3}$	$5,373\ 8 \times 10^{-5}$	$1,328\ 0 \times 10^{-3}$
10	$7,052\ 0 \times 10^{-4}$	$2,260\ 5 \times 10^{-5}$	$5,356\ 0 \times 10^{-4}$
11	$1,432\ 0 \times 10^{-4}$	$7,045\ 4 \times 10^{-6}$	$1,730\ 0 \times 10^{-4}$
12	$1,765\ 0 \times 10^{-5}$	$8,481\ 9 \times 10^{-7}$	$4,881\ 0 \times 10^{-5}$
13	$7,347\ 0 \times 10^{-6}$	$2,972\ 1 \times 10^{-7}$	$2,006\ 0 \times 10^{-5}$
14	$1,747\ 0 \times 10^{-6}$	$9,950\ 9 \times 10^{-8}$	$8,319\ 0 \times 10^{-6}$
15	$5,481\ 0 \times 10^{-7}$	$2,708\ 6 \times 10^{-8}$	$2,358\ 0 \times 10^{-6}$
16	$1,671\ 0 \times 10^{-7}$	$8,352\ 7 \times 10^{-9}$	$6,450\ 0 \times 10^{-7}$
17	$2,112\ 0 \times 10^{-8}$	$1,056\ 9 \times 10^{-9}$	$1,278\ 0 \times 10^{-7}$
18	$2,996\ 0 \times 10^{-9}$	$1,497\ 8 \times 10^{-10}$	$2,466\ 0 \times 10^{-8}$
19	$5,107\ 0 \times 10^{-11}$	$2,552\ 1 \times 10^{-12}$	$9,378\ 0 \times 10^{-9}$
20	$5,730\ 0 \times 10^{-11}$	$2,860\ 8 \times 10^{-12}$	$7,450\ 0 \times 10^{-10}$
21	$4,138\ 0 \times 10^{-14}$	$2,072\ 2 \times 10^{-15}$	$2,426\ 0 \times 10^{-10}$
22	$1,088\ 0 \times 10^{-15}$	$5,420\ 6 \times 10^{-17}$	$2,210\ 0 \times 10^{-13}$
23	$2,454\ 0 \times 10^{-17}$	$1,226\ 8 \times 10^{-18}$	$2,640\ 0 \times 10^{-14}$
24	$7,557\ 0 \times 10^{-17}$	$3,929\ 1 \times 10^{-18}$	$1,380\ 0 \times 10^{-14}$

Coefficients for the fast fission of ^{238}U [see formulae (4), (5), (10) and (11)]

j	$\alpha \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\beta \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\lambda\ (s^{-1})$
1	0	$1,709\ 6 \times 10^{-1}$	$2,905\ 5$
2	$1,231\ 1$	$2,285\ 0 \times 10^{-1}$	$3,288\ 1$
3	$1,148\ 6$	$2,888\ 7 \times 10^{-1}$	$9,380\ 5 \times 10^{-1}$
4	$7,070\ 1 \times 10^{-1}$	$1,538\ 5 \times 10^{-1}$	$3,707\ 3 \times 10^{-1}$
5	$2,520\ 9 \times 10^{-1}$	$4,597\ 1 \times 10^{-2}$	$1,111\ 8 \times 10^{-1}$
6	$7,187\ 0 \times 10^{-2}$	$1,575\ 4 \times 10^{-2}$	$3,614\ 3 \times 10^{-2}$
7	$2,829\ 1 \times 10^{-2}$	$2,926\ 0 \times 10^{-3}$	$1,327\ 2 \times 10^{-2}$
8	$6,838\ 2 \times 10^{-3}$	$4,272\ 0 \times 10^{-4}$	$5,013\ 3 \times 10^{-3}$
9	$1,232\ 2 \times 10^{-3}$	$7,993\ 5 \times 10^{-5}$	$1,365\ 5 \times 10^{-3}$
10	$6,840\ 9 \times 10^{-4}$	$3,230\ 9 \times 10^{-5}$	$5,515\ 8 \times 10^{-4}$
11	$1,697\ 5 \times 10^{-4}$	$1,040\ 8 \times 10^{-5}$	$1,787\ 3 \times 10^{-4}$
12	$2,418\ 2 \times 10^{-5}$	$1,203\ 3 \times 10^{-6}$	$4,903\ 2 \times 10^{-5}$
13	$6,635\ 6 \times 10^{-6}$	$3,211\ 5 \times 10^{-7}$	$1,705\ 8 \times 10^{-5}$
14	$1,007\ 5 \times 10^{-6}$	$4,065\ 1 \times 10^{-8}$	$7,046\ 5 \times 10^{-6}$
15	$4,989\ 4 \times 10^{-7}$	$1,764\ 0 \times 10^{-8}$	$2,319\ 0 \times 10^{-6}$
16	$1,635\ 2 \times 10^{-7}$	$5,777\ 0 \times 10^{-9}$	$6,448\ 0 \times 10^{-7}$
17	$2,335\ 5 \times 10^{-8}$	$8,010\ 3 \times 10^{-10}$	$1,264\ 9 \times 10^{-7}$
18	$2,809\ 4 \times 10^{-9}$	$1,194\ 1 \times 10^{-10}$	$2,554\ 8 \times 10^{-8}$
19	$3,623\ 6 \times 10^{-11}$	$3,262\ 0 \times 10^{-12}$	$8,478\ 2 \times 10^{-9}$
20	$6,457\ 7 \times 10^{-11}$	$3,221\ 3 \times 10^{-12}$	$7,513\ 0 \times 10^{-10}$
21	$4,496\ 3 \times 10^{-14}$	$2,256\ 0 \times 10^{-15}$	$2,418\ 8 \times 10^{-10}$
22	$3,665\ 4 \times 10^{-16}$	$1,835\ 8 \times 10^{-17}$	$2,273\ 9 \times 10^{-13}$
23	$5,629\ 3 \times 10^{-17}$	$2,810\ 7 \times 10^{-18}$	$9,053\ 6 \times 10^{-14}$
24	$7,160\ 2 \times 10^{-17}$	$3,575\ 0 \times 10^{-18}$	$5,609\ 8 \times 10^{-15}$

Coefficients for the thermal fission of ^{241}Pu [see formulae (4), (5), (10) and (11)]

j	$\alpha \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\beta \left(\frac{\text{MeV/s}}{\text{fission}}\right)$	$\lambda\ (s^{-1})$
1	0	0	$2,200\ 0$
2	$6,971\ 9 \times 10^{-1}$	$3,486\ 0 \times 10^{-2}$	$1,022\ 3$
3	$4,949\ 9 \times 10^{-1}$	$2,475\ 0 \times 10^{-2}$	$2,813\ 5 \times 10^{-1}$
4	$1,442\ 2 \times 10^{-1}$	$7,211\ 0 \times 10^{-3}$	$1,092\ 0 \times 10^{-1}$
5	$6,251\ 9 \times 10^{-2}$	$3,126\ 0 \times 10^{-3}$	$4,285\ 7 \times 10^{-2}$
6	$2,963\ 7 \times 10^{-2}$	$1,481\ 9 \times 10^{-3}$	$1,428\ 6 \times 10^{-2}$
7	$4,923\ 6 \times 10^{-3}$	$2,461\ 8 \times 10^{-4}$	$5,191\ 3 \times 10^{-3}$
8	$7,000\ 4 \times 10^{-4}$	$3,500\ 2 \times 10^{-5}$	$1,568\ 6 \times 10^{-3}$
9	$1,298\ 9 \times 10^{-3}$	$6,494\ 5 \times 10^{-5}$	$1,069\ 4 \times 10^{-3}$
10	$-2,354\ 0 \times 10^{-4}$	$-1,177\ 0 \times 10^{-5}$	$5,388\ 3 \times 10^{-4}$
11	$5,846\ 6 \times 10^{-4}$	$2,923\ 3 \times 10^{-5}$	$3,615\ 4 \times 10^{-4}$
12	$6,506\ 6 \times 10^{-5}$	$3,253\ 3 \times 10^{-6}$	$9,215\ 9 \times 10^{-5}$
13	$-5,184\ 0 \times 10^{-5}$	$-2,592\ 0 \times 10^{-6}$	$3,479\ 3 \times 10^{-5}$
14	$5,686\ 1 \times 10^{-5}$	$2,843\ 1 \times 10^{-6}$	$3,113\ 2 \times 10^{-5}$
15	$1,896\ 2 \times 10^{-6}$	$9,481\ 0 \times 10^{-8}$	$7,922\ 6 \times 10^{-6}$
16	$4,410\ 8 \times 10^{-7}$	$2,205\ 4 \times 10^{-8}$	$2,252\ 2 \times 10^{-6}$
17	$1,646\ 0 \times 10^{-7}$	$8,230\ 0 \times 10^{-9}$	$6,294\ 3 \times 10^{-7}$
18	$4,226\ 3 \times 10^{-10}$	$2,113\ 1 \times 10^{-11}$	$2,041\ 9 \times 10^{-7}$
19	$1,677\ 2 \times 10^{-8}$	$8,386\ 0 \times 10^{-10}$	$1,245\ 3 \times 10^{-7}$
20	$-4,632\ 0 \times 10^{-10}$	$-2,316\ 0 \times 10^{-11}$	$4,194\ 1 \times 10^{-8}$
21	$3,878\ 4 \times 10^{-9}$	$1,939\ 2 \times 10^{-10}$	$2,479\ 1 \times 10^{-8}$
22	$1,048\ 1 \times 10^{-10}$	$5,240\ 5 \times 10^{-12}$	$1,154\ 7 \times 10^{-8}$
23	$-1,791\ 0 \times 10^{-12}$	$-8,955\ 0 \times 10^{-14}$	$3,875\ 9 \times 10^{-9}$
24	$5,247\ 6 \times 10^{-11}$	$2,623\ 8 \times 10^{-12}$	$7,444\ 0 \times 10^{-10}$