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ANSI/ANS-5.1-2014



ANS

Decay Heat Power in Light Water Reactors

REAFFIRMED

February 5, 2019

ANSI/ANS-5.1-2014 (R2019)

ANSI/ANS-5.1-2014

An American National Standard

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ERRATUM

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Decay Heat Power in Light Water Reactors

A typographical error was identified on page 30, formula (28). Time should be 10^4 s not 10^{-4} s.” The corrected formula is provided below:

6 Total decay heat power

The total decay heat power from the fission products and actinides is calculated as

$$P_T(t, T) = P'_d(t, T) + P_{dc}(t, T) + P_{dHE}(t, T) + P_{dA}(t, T), \quad (27)$$

where

$$P_{dc}(t, T) = \begin{cases} P'_d(t, T) \cdot G(t), & t \leq 10^4 \text{ s} \\ P_{dCs}(t, T) + P_{dE}(t, T), & t > 10^4 \text{ s} \end{cases}. \quad (28)$$

The total uncertainty is determined from the uncertainty in the fission product decay heat power without neutron capture in fission products, $\Delta P'_d(t, T)$, as described in Eq. (6), and the uncertainty in the operating power, ΔP , as described in Eq. (7). The other terms in Eq. (27) are defined to provide conservative overestimates of their contributions to the decay heat power, and the uncertainties in these terms are therefore not included in the total uncertainty.

**American National Standard
Decay Heat Power
in Light Water Reactors**

Secretariat
American Nuclear Society

Prepared by the
**American Nuclear Society
Standards Committee
Working Group ANS-5.1**

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American National Standard

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Foreword (This Foreword is not a part of American National Standard “Decay Heat Power in Light Water Reactors,” ANSI/ANS-5.1-2014.)

This American National Standard provides values for the decay heat power from fission products and actinides following the shutdown of light water reactors operated with nuclear fuel consisting of uranium. The energy released in the fission process is divided into (1) prompt energy from the kinetic energy of fission fragments, neutrons, and gamma rays from prompt de-excitation of fission products and (2) delayed energy from beta particles and gamma rays emitted from the decay of fission products.

The development of this standard was initiated due to the importance of energy release after reactor shutdown and the need for accurate data to evaluate fuel rod heating during a loss-of-coolant accident. The ANS Standards Subcommittee first proposed the adoption of a new standard on decay heat power in October, 1971. Following minor revisions in 1973, it was submitted to the American National Standards Institute but remained as a draft standard. After significant technical developments based on data from new experimental programs, the draft standard was revised and approved and released as the 1979 standard. Since then, it was reaffirmed in 1985, revised in 1994, and revised again in 2005. The revisions since 1979 have been guided largely by recommendations made by Dickens, England, and Schenter on future improvements to the standard.¹⁾ A detailed technical summary of the development of the standard and revisions is provided as an Appendix to this standard.

The standard prescribes methods that enable the calculation of fission product decay heat power and uncertainty with accuracies comparable to those of summation codes but without the need for complex calculations. Fission product decay heat values are provided for thermal neutron-induced fission of ^{235}U , ^{239}Pu , and ^{241}Pu and fast fission of ^{238}U .

As revised, this standard provides better guidance on methods and implementation, an improved representation of uncertainties in the fission product decay heat values, and an improved method for the neutron capture correction. Also included, for the first time, is a complete estimate of all actinide contributions to decay heat power. The changes in this revision do not alter the tabular data for standard fission product decay heat power and uncertainty values from the 1994 and 2005 standards, but they do include several recommendations for near-term improvements to the standard identified by Dickens, England, and Schenter.

Relationship to Other Standards

ANSI/ANS-19.3.4-2002 (R2008), “Determination of Thermal Energy Deposition Rates in Nuclear Reactors”

Proposed American National Standard ANS-19.8, “Fission-Product Yields for ^{235}U , ^{238}U , and ^{239}Pu ” (in draft form)

ANSI/ANS 19.1-2002 (R2011), “Nuclear Data Sets for Reactor Design Calculations”

This standard might reference documents and other standards that may have been superseded or withdrawn at the time this standard is applied.

¹⁾ J. K. Dickens, T. R. England, and R. E. Schenter, “Current Status and Proposed Improvements to the ANSI/ANS-5.1 American National Standard for Decay Heat Power in Light Water Reactors,” *Nucl. Safety*, **32**, 209 (1991).

This standard does not incorporate the concepts of generating risk-informed insights, performance-based requirements, or a graded approach to quality assurance. The user is advised that one or more of these techniques could enhance the application of this standard.

The working group acknowledges the substantial efforts of earlier working groups in establishing and maintaining this standard. The working group specifically acknowledges the significant contributions made to the standard by the late J. Kirk Dickens and Robert Schenter, who passed away before this standard was issued. Both of these working group members played key roles in the development and advancement of the standard and provided a roadmap for future improvements of the standard that was used to guide this revision.

Working Group ANS-5.1 of the Standards Committee of the American Nuclear Society had the following membership at the time of its approval of this revision of the standard:

I. C. Gauld (Chair), *Oak Ridge National Laboratory*
M. C. Brady Raap (Past Chair for ANSI/ANS-5.1-2005), *Pacific Northwest National Laboratory*
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E. R. Knuckles, *Individual*
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H. Trellue, *Los Alamos National Laboratory*
S. Wang, *Westinghouse Electric Company, LLC*
T. Yoshida, *Musashi Institute of Technology*
D. Ziabletsev, *AREVA Inc.*

The membership of Subcommittee ANS-19 at the time of the review and approval of this standard was as follows:

D. M. Cokinos (Chair), *Brookhaven National Laboratory*
C. T. Rombough (Secretary), *CTR Technical Services*

A. Attard, *Individual*
S. Baker, *Transware*
W. H. Bell, *South Carolina Electric & Gas Co.*
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E. R. Knuckles, *Individual*
B. Rouben, *Individual*
A. Weitzberg, *Individual*

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A. Weitzberg, (Vice Chair), *Individual*

F. A. Alpan, *Westinghouse Electric Company, LLC*
R. S. Amato, *Bechtel Marine Propulsion Corporation*
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Decay Heat Power in Light Water Reactors

1 Scope and purpose

1.1 Scope

This standard sets forth values for the decay heat power from fission products and actinides following shutdown of light water reactors (LWRs) using nuclear fuel initially containing ^{235}U and ^{238}U . The decay heat power from fission products is presented in tables and equivalent analytical representations. Contributions from the decay of ^{239}U and ^{239}Np and the contributions from all other actinides are represented separately. Methods are described that account for the reactor operating history, for the effect of neutron capture in fission products, and for assessing the uncertainty in the resultant decay heat power.

The standard applies to decay times of up to 10^{10} s after shutdown.

1.2 Purpose and application

This standard provides bases for determining the decay heat power and its uncertainty following shutdown of LWRs. The information in this standard can be used in the design, performance evaluation, and assessment of the safety of LWRs.

The methods prescribed in this standard enable the calculation of fission product decay heat power with accuracies comparable to those of summation codes but without the need for complex calculations. The fission product decay heat power values in this standard have the advantage of being developed directly from experimental measurements for time periods $<10^5$ s after fission. Therefore, this standard can be used as the basis for comparison with results of alternate methods for determining fission product decay heat power.¹⁾

2 Range of application

2.1 Limitations

The standard methods for evaluating decay heat described herein are applicable to LWRs containing ^{235}U as the initial major fissile material and ^{238}U as the fertile material. The contributions from the fission of ^{235}U , ^{238}U , ^{239}Pu , and ^{241}Pu are treated explicitly; other fissionable nuclides are accounted for by treating them as ^{235}U . The application of this standard to mixed oxide or other recycled nuclear fuels is not supported.

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

2.2 Standard decay heat power representation

Standard fission product decay heat power values are provided in tabular form and as analytical representations of the thermal reactor neutron spectrum fission of ^{235}U , ^{239}Pu , and ^{241}Pu and for fast fission of ^{238}U at various times after fission. Uncertainties are provided for each shutdown time for each of the tabulations.

¹⁾ Examples of the use of the standard methods are presented in Appendix B.

The standard values do not account for neutron capture in fission products. A method is prescribed separately to account for the effect of neutron capture in fission products for shutdown times less than 10^4 s; it uses a multiplying factor that depends upon reactor operating time, total fissions per initial fissile atom, and the time after shutdown. For decay times beyond 10^4 s, the effect of neutron capture is determined explicitly for ^{134}Cs ; the contribution from neutron capture in other fission products is determined using an upper bound multiplying factor for decay times up to 10^{10} s.

Methods are prescribed for obtaining the total fission product decay heat power and the associated uncertainty for finite reactor operating times using analytic representations of the standard values. Alternate methods are prescribed whereby the decay heat power may be obtained using tabulated values based on an infinite reactor operation representation.

Actinide decay heat power is determined for ^{239}U and ^{239}Np and separately for other actinides. The ^{239}U and ^{239}Np are large contributors to the decay heat power, particularly for decay times $<10^6$ s after shutdown, which are important to reactor safety assessments. The contribution of other actinides is treated by the standard using a correction factor developed for conservative operating conditions. As the contributions from ^{239}U , ^{239}Np , and the fission products decrease with increasing decay time, the remaining actinides become a much larger component of the total decay heat. Consequently, the prescribed decay heat power will become increasingly conservative due to the bounding treatment of the actinides (other than ^{239}U and ^{239}Np) in this standard.

The user may employ alternate methods or data for calculating the individual components of the decay heat power than those prescribed in this standard (other than fission products), provided that their validity is established. For the fission product contribution, alternate methods may be validated by comparison with this standard.

2.3 Shutdown times $>10^{10}$ s

This standard applies to shutdown times up to 10^{10} s and should not be extrapolated to $t > 10^{10}$ s.

2.4 Energy distribution

This standard relates local production of decay heat power in the shutdown condition to local fission power during the operating condition. The variation in the spatial energy deposition distribution of the decay heat power caused by gamma-ray energy transport from the local region of production is problem- and time-dependent and is beyond the scope of this standard. It is left to the users of this standard to assess the influence of the spatial decay heat power distribution.

3 Definition of terms

3.1 Shall, should, and may

The word “shall” is used to denote a requirement, the word “should” is used to denote a recommendation, and the word “may” is used to denote permission, neither a requirement nor a recommendation.

3.2 Symbols

The symbols used in this standard are defined below:

T : Total operating period, including intermediate periods at zero power (s).

T_{eff} : Total operating period, excluding intermediate periods at zero power (s).

t : Time after shutdown (cooling time; s).

∞ : Infinite irradiation time ($T \equiv 10^{13}$ s for computational purposes).

$f_i(t)$: Decay heat power t seconds after a fission pulse from fissionable nuclide i [(MeV/s)/fission].

$\Delta f_i(t)$: One standard deviation in $f_i(t)$ [(MeV/s)/fission].

- $F_i(t, T)$: Decay heat power t seconds after an operating period of T seconds at constant fission rate of nuclide i in the absence of neutron capture in fission products [(MeV/s)/(fission/s)].
- $\Delta F_i(t, T)$: One standard deviation in $F_i(t, T)$ [(MeV/s)/(fission/s)].
- Q_i : Total recoverable energy²⁾ associated with one fission of nuclide i (MeV/fission).
- ΔQ_i : One standard deviation in Q_i (MeV/fission).
- P_{ia} : Average power from the fissioning of nuclide i during operation period T_a (MeV/s).
- ΔP_{ia} : One standard deviation in P_{ia} (MeV/s).
- α : An index specifying an operating period at constant power.
- $P_d(t, T)$: Total fission product decay heat power at t seconds after shutdown from an operating history of T seconds duration (MeV/s).
- $P'_d(t, T)$: Total fission product decay heat power corresponding to $P_d(t, T)$: but uncorrected for neutron capture in fission products (MeV/s).
- $P'_{di}(t, T)$: Fission product decay heat power contribution to $P'_d(t, T)$ by the i 'th fissionable nuclide, uncorrected for neutron capture in fission products (MeV/s).
- $P_{dHE}(t, T)$: The contribution of actinide decay heat power contributed by ^{239}U and ^{239}Np (MeV/s).
- $P_{dA}(t, T)$: The contribution of actinide decay heat power contributed by heavy elements excluding ^{239}U and ^{239}Np (MeV/s).
- $P_{dC}(t, T)$: The contribution of decay heat power from neutron capture in all fission products (MeV/s).
- $P_{dCs}(t, T)$: The contribution of ^{134}Cs to the decay heat power (MeV/s).
- $P_{dE}(t, T)$: The contribution to the decay heat power from neutron capture in fission products excluding ^{134}Cs (MeV/s).
- $G(t)$: The factor that accounts for neutron capture in fission products for $t \leq 10^4$ s.
- $H(t)$: The factor that accounts for neutron capture in fission products for $t > 10^4$ s, excluding the contribution from ^{134}Cs .
- $A(t)$: The factor that accounts for the contribution from actinides excluding ^{239}U and ^{239}Np .
- ψ : Fissions per initial fissile atom (dimensionless).

4 Fission product decay heat power

4.1 General

The data on fission product decay heat power from the fission of nuclide i is represented by $f_i(t)$, the decay heat power per fission following an instantaneous fission pulse of a significant number of fission events. The method for applying these data for the calculation of fission product decay heat power for an irradiation interval of time T followed by a shutdown time t is presented in two ways in this standard. The first method of presentation is represented in terms of $F_i(t, T)$, the decay heat power from fission products produced at a constant rate over an operating interval T . The second method of presentation is $F_i(t, \infty)$, the decay heat power from fission products produced at a constant rate over an infinitely long operating interval T . Both $F_i(t, T)$ and $F_i(t, \infty)$ exclude the contribution to fission product decay heat power from neutron absorption in the fission products.

²⁾ Includes fission fragment and neutron kinetic energy, prompt γ energy, γ and β radiation from complete decay of fission products, and γ and β radiation from capture reactions in all fuel, coolant, and structural materials.

4.2 Determining decay heat power and uncertainty from $F_i(t, T)$

The average fission product decay heat power per fission following an instantaneous fission pulse is represented as $f_i(t)$. The data representing $f_i(t)$ and its assigned one sigma uncertainty, $\Delta f_i(t)$ for the thermal fission of ^{235}U and ^{239}Pu are shown in Tables 1 and 2, respectively; the data for fast fission of ^{238}U and thermal fission of ^{241}Pu are given in Tables 3 and 4, respectively.

Table 1 – Tabular data for standard decay heat power for pulse thermal fission of ^{235}U

Time after shutdown, $t(\text{s})$	Decay heat power $f(t)$ [(MeV/s)/fission]	One sigma uncertainty $\Delta f(t)$ [(MeV/s)/fission]	One sigma uncertainty (percent)
1.0E+00	8.219E-01 ¹⁾	1.282E-01	15.6
1.5E+00	6.677E-01	0.661E-01	9.9
2.0E+00	5.600E-01	0.386E-01	6.9
4.0E+00	3.413E-01	0.147E-01	4.3
6.0E+00	2.447E-01	0.086E-01	3.5
8.0E+00	1.882E-01	0.058E-01	3.1
1.0E+01	1.513E-01	0.048E-01	3.2
1.5E+01	9.956E-02	0.259E-02	2.6
2.0E+01	7.341E-02	0.176E-02	2.4
4.0E+01	3.544E-02	0.071E-02	2.0
6.0E+01	2.322E-02	0.044E-02	1.9
8.0E+01	1.685E-02	0.032E-02	1.9
1.0E+02	1.295E-02	0.023E-02	1.8
1.5E+02	7.866E-03	0.149E-03	1.9
2.0E+02	5.480E-03	0.104E-03	1.9
4.0E+02	2.383E-03	0.045E-03	1.9
6.0E+02	1.581E-03	0.028E-03	1.8
8.0E+02	1.195E-03	0.023E-03	1.9
1.0E+03	9.587E-04	0.173E-04	1.8
1.5E+03	6.345E-04	0.114E-04	1.8
2.0E+03	4.648E-04	0.084E-04	1.8
4.0E+03	1.977E-04	0.038E-04	1.9
6.0E+03	1.152E-04	0.021E-04	1.8
8.0E+03	7.891E-05	0.142E-05	1.8
1.0E+04	5.897E-05	0.106E-05	1.8
1.5E+04	3.419E-05	0.055E-05	1.6
2.0E+04	2.302E-05	0.032E-05	1.4
4.0E+04	9.329E-06	0.131E-06	1.4
6.0E+04	5.372E-06	0.075E-06	1.4
8.0E+04	3.558E-06	0.050E-06	1.4
1.0E+05	2.579E-06	0.044E-06	1.7
1.5E+05	1.434E-06	0.029E-06	2.0

Table 1 – Tabular data for standard decay heat power for pulse thermal fission of ^{235}U (Cont'd)

Time after shutdown, t(s)	Decay heat power $f(t)$ [(MeV/s)/fission]	One sigma uncertainty $\Delta f(t)$ [(MeV/s)/fission]	One sigma uncertainty (percent)
2.0E+05	9.465E-07	0.189E-07	2.0
4.0E+05	3.981E-07	0.080E-07	2.0
6.0E+05	2.663E-07	0.053E-07	2.0
8.0E+05	2.015E-07	0.040E-07	2.0
1.0E+06	1.606E-07	0.032E-07	2.0
1.5E+06	1.039E-07	0.021E-07	2.0
2.0E+06	7.527E-08	0.151E-08	2.0
4.0E+06	3.143E-08	0.063E-08	2.0
6.0E+06	1.818E-08	0.036E-08	2.0
8.0E+06	1.277E-08	0.026E-08	2.0
1.0E+07	9.829E-09	0.197E-09	2.0
1.5E+07	5.804E-09	0.116E-09	2.0
2.0E+07	3.673E-09	0.073E-09	2.0
4.0E+07	1.041E-09	0.021E-09	2.0
6.0E+07	5.445E-10	0.109E-10	2.0
8.0E+07	3.438E-10	0.069E-10	2.0
1.0E+08	2.342E-10	0.047E-10	2.0
1.5E+08	1.204E-10	0.024E-10	2.0
2.0E+08	8.854E-11	0.177E-11	2.0
4.0E+08	6.634E-11	0.133E-11	2.0
6.0E+08	5.633E-11	0.113E-11	2.0
8.0E+08	4.813E-11	0.096E-11	2.0
1.0E+09	4.127E-11	0.083E-11	2.0
1.5E+09	2.832E-11	0.057E-11	2.0
2.0E+09	1.951E-11	0.039E-11	2.0
4.0E+09	4.424E-12	0.088E-12	2.0
6.0E+09	1.006E-12	0.022E-12	2.2
8.0E+09	2.305E-13	0.055E-13	2.4
1.0E+10	5.405E-14	0.151E-14	2.8
1.5E+10	2.662E-15	0.106E-15	4.0
2.0E+10	1.068E-15	0.068E-15	6.4
4.0E+10	8.845E-16	0.265E-16	3.0
6.0E+10	8.811E-16	0.264E-16	3.0
8.0E+10	8.789E-16	0.264E-16	3.0
1.0E+11	8.766E-16	0.272E-16	3.1
1.5E+11	8.710E-16	0.270E-16	3.1
2.0E+11	8.654E-16	0.277E-16	3.2

Table 1 – Tabular data for standard decay heat power for pulse thermal fission of ^{235}U (Cont'd)

Time after shutdown, $t(\text{s})$	Decay heat power $f(t)$ [(MeV/s)/fission]	One sigma uncertainty $\Delta f(t)$ [(MeV/s)/fission]	One sigma uncertainty (percent)
4.0E+11	8.434E-16	0.278E-16	3.3
6.0E+11	8.221E-16	0.280E-16	3.4
8.0E+11	8.015E-16	0.273E-16	3.4
1.0E+12	7.814E-16	0.273E-16	3.5
1.5E+12	7.339E-16	0.301E-16	4.1
2.0E+12	6.898E-16	0.317E-16	4.6
4.0E+12	5.430E-16	0.358E-16	6.6
6.0E+12	4.340E-16	0.347E-16	8.0
8.0E+12	3.526E-16	0.300E-16	8.5
1.0E+13	2.916E-16	0.236E-16	8.1

¹⁾ Read as 8.219×10^{-1} .

NOTE—Data below double line: Data for t greater than 10^{10} s were used to develop the tabulated data in Tables 9, 10, 11, and 12; they are not to be interpreted as standard decay heat values for these times.

Table 2 – Tabular data for standard decay heat power for pulse thermal fission of ^{239}Pu

Time after shutdown, $t(\text{s})$	Decay heat power $f(t)$ [(MeV/s)/fission]	One sigma uncertainty $\Delta f(t)$ [(MeV/s)/fission]	One sigma uncertainty (percent)
1.0E+00	5.299E-01 ¹⁾	1.325E-01	25.0
1.5E+00	4.494E-01	0.629E-01	14.0
2.0E+00	3.872E-01	0.387E-01	10.0
4.0E+00	2.430E-01	0.134E-01	5.5
6.0E+00	1.750E-01	0.089E-01	5.1
8.0E+00	1.358E-01	0.067E-01	4.9
1.0E+01	1.102E-01	0.054E-01	4.9
1.5E+01	7.378E-02	0.339E-02	4.6
2.0E+01	5.525E-02	0.193E-02	3.5
4.0E+01	2.801E-02	0.098E-02	3.5
6.0E+01	1.875E-02	0.066E-02	3.5
8.0E+01	1.386E-02	0.046E-02	3.3
1.0E+02	1.080E-02	0.032E-02	3.0
1.5E+02	6.687E-03	0.207E-03	3.1
2.0E+02	4.717E-03	0.142E-03	3.0
4.0E+02	2.217E-03	0.069E-03	3.1
6.0E+02	1.523E-03	0.046E-03	3.0
8.0E+02	1.170E-03	0.035E-03	3.0
1.0E+03	9.504E-04	0.295E-04	3.1

Table 2 – Tabular data for standard decay heat power for pulse thermal fission of ^{239}Pu (Cont'd)

Time after shutdown, $t(\text{s})$	Decay heat power $f(t)$ [(MeV/s)/fission]	One sigma uncertainty $\Delta f(t)$ [(MeV/s)/fission]	One sigma uncertainty (percent)
1.5E+03	6.362E-04	0.197E-04	3.1
2.0E+03	4.614E-04	0.138E-04	3.0
4.0E+03	1.847E-04	0.042E-04	2.3
6.0E+03	1.016E-04	0.024E-04	2.4
8.0E+03	6.619E-05	0.172E-05	2.6
1.0E+04	4.789E-05	0.153E-05	3.2
1.5E+04	2.710E-05	0.114E-05	4.2
2.0E+04	1.828E-05	0.088E-05	4.8
4.0E+04	7.878E-06	0.347E-06	4.4
6.0E+04	4.874E-06	0.224E-06	4.6
8.0E+04	3.366E-06	0.162E-06	4.8
1.0E+05	2.496E-06	0.125E-06	5.0
1.5E+05	1.436E-06	0.072E-06	5.0
2.0E+05	9.775E-07	0.489E-07	5.0
4.0E+05	4.307E-07	0.215E-07	5.0
6.0E+05	2.812E-07	0.141E-07	5.0
8.0E+05	2.072E-07	0.104E-07	5.0
1.0E+06	1.616E-07	0.081E-07	5.0
1.5E+06	9.989E-08	0.499E-08	5.0
2.0E+06	7.022E-08	0.351E-08	5.0
4.0E+06	2.819E-08	0.141E-08	5.0
6.0E+06	1.599E-08	0.080E-08	5.0
8.0E+06	1.112E-08	0.056E-08	5.0
1.0E+07	8.594E-09	0.430E-09	5.0
1.5E+07	5.286E-09	0.264E-09	5.0
2.0E+07	3.567E-09	0.178E-09	5.0
4.0E+07	1.336E-09	0.067E-09	5.0
6.0E+07	7.758E-10	0.388E-10	5.0
8.0E+07	4.950E-10	0.247E-10	5.0
1.0E+08	3.273E-10	0.164E-10	5.0
1.5E+08	1.378E-10	0.069E-10	5.0
2.0E+08	7.858E-11	0.393E-11	5.0
4.0E+08	4.367E-11	0.218E-11	5.0
6.0E+08	3.703E-11	0.185E-11	5.0
8.0E+08	3.193E-11	0.160E-11	5.0
1.0E+09	2.756E-11	0.138E-11	5.0
1.5E+09	1.909E-11	0.095E-11	5.0