1.5. Components of Energy Release Due to Fission (MT=458)

The energy released in fission is carried by fission products, neutrons, gammas, betas (+ and -), and neutrinos and anti-neutrinos. Here, fission products include all charged particles that are emitted promptly, since for energy-deposition calculations all such particles have short ranges and are usually considered to lose their energy locally. Neutrons and gammas transport their energy elsewhere and need to be considered separately. In addition, some gammas and neutrons are delayed, and in a shut-down assembly one needs to know the amount of energy tied up in these particles and the rate at which it is released from the metastable nuclides or precursors. The neutrino energy is lost completely in most applications, but is part of the Q-value. As far as the betas are concerned, prompt betas, being charged, deposit their energy locally with the fission fragments, and their prompt energies are included with the fission product energy.

This format recognizes nine specific components for fission energy release. The nomenclature used to define these nine energy release terms is:

ET	Sum of all the partial energies that follow. This sum is the total energy release per fission and equals the Q value.
EFR	Kinetic energy of the fission products (following prompt neutron emission from the fission fragments).
ENP	Kinetic energy of the prompt fission neutrons.
END	Kinetic energy of the delayed fission neutrons.
EGP	Total energy released by the emission of prompt γ rays.
EGD	Total energy released by the emission of delayed γ rays.
EB	Total energy released by delayed β's.
ENU	Energy carried away by neutrinos.
ER	Total energy less the energy of the neutrinos (ET – ENU); sometimes referred to as the pseudo-Q value and equal to the Q value in File 3, MT=18.

The total energy release due to fission is an incident energy dependent quantity, as are many, if not all, of the constituent terms.

There are two formats available to represent these energy dependencies. From the work of Sher and Beck (Reference 1), the energy dependence is given as

$$E_i(E_{inc}) = E_i(0) - \delta E_i(E_{inc})$$

where

$E_i(E_{inc})$ = fission energy release for each of the nine components;

$E_i(0)$ = a constant, one for each of the nine fission energy release terms. These constants and their uncertainties are specified via the NPLY = 0 format option, defined in Section 1.5.1;

$\delta E_i(E_{inc})$ = a function that allows for the definition of the energy dependence of this fission energy component. These functions can not be determined based upon the data given in the evaluated file; rather unique functions are defined for the various fission energy release terms, as follows:

$\delta ET = -[1.057E_{inc} - 8.07*(\text{nubar}(E_{inc}) - \text{nubar}(0)]$
$\delta EB = 0.075E_{inc}$
$\delta EGD = 0.075E_{inc}$
$\delta ENU = 0.100E_{inc}$
$\delta EFR = 0$
$\delta ENP = -[1.307E_{inc} - 8.07*(\text{nubar}(E_{inc}) - \text{nubar}(0)]$
$\delta EGP = 0$

However, a recent study of relevant experimental data, supplemented with model calculations, by Madland (Reference 2) has shown that the δEFR and δEGP terms are not zero, but instead have definite dependencies upon the incident neutron energy, E_{inc}. This means that the remaining δ values above are accounting for these dependencies in addition to their own dependencies. In short, the calculations of individual energy release values are suspect even though the total energy release, ET, is substantially correct. Madland concludes that the energy dependence for the various fission energy release terms may be accurately represented with simple polynomial expansions in incident neutron energy. As such, the energy dependencies are completely defined by specifying the coefficients of NPLYth order polynomials:

$$E_i(E_{inc}) = c_0 + c_1*E_{inc} + c_2*E^2_{inc} + \ldots$$

The polynomial expansion coefficients and their uncertainties are specified via the NPLY ≠ 0 option in Section 1.5.1. With the Madland representation, the complete energy release may be determined solely from the data tabulated by the evaluator, without regard to the various functional forms defined above.

1.5.1 Formats

The structure of this section always starts with a HEAD record and ends with a SEND record. The section contains no subsections and only one LIST record.

The structure of a section takes one of two forms. When NPLY=0, the format is:

```
[MAT, 1, 458/     ZA,    AWR,       0,         0,       0,        0] HEAD
[MAT, 1, 458/    0.0,    0.0,       0,  NPLY=0,  N1=18,     N2=9 /
                 EFR,   ΔEFR,     ENP,      ΔENP,    END,     ΔEND
                 EGP,   ΔEGP,     EGD,      ΔEGD,     EB,      ΔEB
                 ENU,   ΔENU,      ER,       ΔER,     ET,      ΔET] LIST
[MAT, 1,   0/    0.0,    0.0,       0,         0,       0,        0] SEND
```

where the Δ terms represent the uncertainties on the preceding quantity. These data are used in conjunction with the Sher and Beck formulas from Section 1.5 to determine the energy release.

For the polynomial expansion representation, NPLY represents the highest polynomial order needed to define any of the energy release components. The size of the list record is 18*(NPLY+1). The first 18 values are nine pairs of “c_0” and “Δc_0” terms, followed by nine pairs of “c_1” and “Δc_1” terms, and continuing through the maximum polynomial order.

[MAT, 1, 458/ ZA, AWR, 0, 0, 0, 0] HEAD
[MAT, 1, 458/ 0.0, 0.0, 0, NPLY, 18*(NPLY+1), 9*(NPLY+1) /
$c_0^{EFR}, \Delta c_0^{EFR}, c_0^{ENP}, \Delta c_0^{ENP}, c_0^{END}, \Delta c_0^{END}$
$c_0^{EGP}, \Delta c_0^{EGP}, c_0^{EGD}, \Delta c_0^{EGD}, c_0^{EB}, \Delta c_0^{EB}$
$c_0^{ENU}, \Delta c_0^{ENU}, c_0^{ER}, \Delta c_0^{ER}, c_0^{ET}, \Delta c_0^{ET}$
$c_1^{EFR}, \Delta c_1^{EFR}, c_1^{ENP}, \Delta c_1^{ENP}, c_1^{END}, \Delta c_1^{END}$
$c_1^{EGP}, \Delta c_1^{EGP}, c_1^{EGD}, \Delta c_1^{EGD}, c_1^{EB}, \Delta c_1^{EB}$
$c_1^{ENU}, \Delta c_1^{ENU}, c_1^{ER}, \Delta c_1^{ER}, c_1^{ET}, \Delta c_1^{ET}$
…] LIST
[MAT, 1, 0/ 0.0, 0.0, 0, 0, 0, 0] SEND

As with the NPLY = 0 option, the Δ terms represent the uncertainties on the preceding quantity.

1.5.2 Procedures

This section should be used for fertile and fissile isotopes only.

Consistency should be maintained between the Q values in File 3, the energies calculated from File 5 and 15 and the energies calculated from the data given here. Note that ER = pseudo-Q for fission (MT=18) in File 3.

Other components are not so readily determined or checked. When the NPLY=0 option is used, the procedure should be that File 5 and File 15 data take precedent, whenever possible. That is, “prompt” fission neutron energy calculated from File 5 spectra from MT=18 should be used in File 1; the same holds true for the delayed neutron spectra given in File 5, MT=455. The “prompt” gamma energy calculated from File 15 (MT=18 for fission) should be input into File 1; this is the prompt gammas due to the fission process. When NPLY ≠ 0, the nature of the polynomial fitting process may yield small differences between the values calculated from the polynomial coefficients and the values calculated using the spectral data from Files 5 and 15.

These quantities should be calculated at the lowest energy given in the Files for MT=18 except for fissile isotopes for which the thermal spectra should be used. For fertile materials, the spectrum given at threshold would be appropriate. Note that the File 5 spectra for MT=18 should be used with $\bar{\upsilon}$ prompt (not $\bar{\upsilon}$ total) for the fission neutrons. MT=455 in File 5 contains the delayed fission neutron spectra.

In many reactor applications, the time dependent energy deposition rates are required rather than the components of the total energy per fission which are the values given in this MT. Time-dependent energy deposition parameters can be obtained from the six-group spectra in File 5 (MT=455) for delayed neutrons. Codes such as CINDER, RIBD, and ORIGEN must be used, however, to obtain more detailed information on the delayed neutrons and all time-dependent parameters for the betas and the gammas due to the fission process.

The time-integrated energies for delayed neutrons, delayed gammas, and delayed betas as calculated from the codes listed above may not always agree with the energy components given in File 1. The File 1 components must sum to ET (the total energy released per fission).

In heating calculations, the energy released in all nuclear reactions besides fission, principally the gamma-energy released in neutron radiative capture, enters analogously to the various fission energy components. Thus the (n,γ) energy-release would be equal to the Q-value in File 3, MT=102, for the capturing nuclide. The capture gammas can be prompt or delayed, if branching to isomeric states is involved, and this is relevant to various fission- and burnup-product calculations. The "sensible energy" in a heating calculation is the sum of ER, defined previously, plus the energy released in all other reactions.

1.6. References for Chapter 1.

1. R. Sher and C. Beck, Electric Power Research Institute report **EPRI-NP-1771** (1981).
2. D.G. Madland, ***Nucl.Phys. A772*** (2006) 113-137.