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Report

Modification of ENDF Law 4/44/61 Sampling in MCNP6

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1 Introduction

During testing of ENDF/B-VII.1 data at Los Alamos National Laboratory (LANL) an issue was discovered with how MCNP sampled data from ENDF Law 4 (or Laws 44 or 61, which are extensions thereof, but Law 4 will be used to imply the others), the Tabular Distribution. A new sampling scheme in MCNP6 was implemented, and is more robust and has a more mathematically correct interpolation scheme. The consequence of this modification is that particle tracking may change with neutron or (more noticeably) in coupled neutron-photon problems where Law 4 data has an outgoing energy distribution represented as both discrete lines and a continuum. The effects on tally results are expected to be small.

An overview of ENDF Law 4 is given, the issues with MCNP are discussed, the modifications to MCNP6 that were made are explained, and the effect on test problems is shown.

2 Overview of Law 4

ENDF Law 4 is tabular data of outgoing energy and angular distributions given on an incident energy grid. The outgoing energies may consist of discrete lines, continuous distributions, or a mixture of both. The design specifications in MCNP insist that the number of discrete lines must match, and a linear interpolation scheme is used for the probability functions between points on the incident energy grids. The continua, however, may be on differing outgoing energy grids, and, for this reason, unit-base interpolation is used to preserve thresholds.

First, the incident energy E is located on the incident energy grid. The left point of the grid containing E is taken to be E_i and the point on the right side is E_{i+1}. The interpolation fraction r is found by

$$r = \frac{E - E_i}{E_{i+1} - E_i}. \tag{1}$$

If discrete lines are present, MCNP tries to sample a discrete line. Let $c_{i,k}$ be the cumulative density of the kth discrete line at incident energy point i. A random number ξ_1 is sampled from $[0, 1)$ and the kth discrete line is chosen if

$$c_{i,k} + r(c_{i+1,k} - c_{i,k}) < \xi_1 \le c_{i,k+1} + r(c_{i+1,k+1} - c_{i,k+1}). \tag{2}$$

If ξ_1 falls within the discrete part of the table, the outgoing energy is sampled as

$$E_f = E_{i,k} + r(E_{i+1,k} - E_{i,k}). \tag{3}$$

Should ξ_1 fall outside the discrete part of the table, then the continuum must be sampled. Because the outgoing energy grids on the continuum do not have to line up, a unit-base interpolation is performed. The outgoing energy of the continuum is sampled either from bin i or $i + 1$, which is chosen randomly. This sampled energy is then interpolated using the interpolation factor r.

Let ℓ be the index for the outgoing energy continuum grid selected. The old behavior in MCNP was to sample ℓ solely based on the magnitude of the interpolation factor r. The new behavior in MCNP6 is to sample ℓ not just on the interpolation factor, but weighted by the probabilities of sampling each continuum. More detail on this is given in the section that discusses the changes.

Given an ℓ the random number ξ_1 is scaled to sample on the chosen outgoing energy grid. Alternatively, a new random number could have been found and scaled to match the boundaries of the continuum, but this is not necessary so long as ξ_1 is scaled consistently. The intermediate outgoing energy E' is sampled from either a histogram or (most commonly) a linear-linear interpolation.

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The final outgoing energy E_f is calculated from a unit-base interpolation. Let

$$E_b = E_{i,1} + r(E_{i+1,1} - E_{i,1}), \tag{4}$$

$$E_t = E_{i,M} + r(E_{i+1,N} - E_{i,M}), \tag{5}$$

be the bottom and top energies, where 1 here is the index for the lower energy bound of each continua, and M and N are the indices for the maximum energy bound of continua i and $i+1$ respectively. E_f is calculated by

$$E_f = E_b + (E_t - E_b)\frac{E' - E_{\ell,1}}{E_{\ell,(M,N)} - E_{\ell,1}}. \tag{6}$$

Note the (M, N) subscript here means M for $\ell = i$ and N for $\ell = i + 1$.

The outgoing direction cosine is sampled independent of the outgoing energy, and is based on tabular data.

3 Issue in MCNP Sampling

During testing by the LANL Nuclear Data Team of ENDF/B-VII.1 data, an issue was found in MCNP6-Beta3 and previous versions of MCNP that would result in an error in sampling ENDF Law 4 data tables. The issue occurs when ENDF Law 4 is used and the outgoing energies are represented both as discrete lines and a continuum. While the ACE file specification says that the number of discrete lines at all incident energy grid points must be the same, there is no restriction on the energy resolution or even the presence of a continuum at each incident energy grid point. MCNP assumed that if continua are present at some incident energies, then there must be continua present at all other incident energies. For physical reasons, i.e., all emissions may be described as discrete lines for some energies but not for others, this need not be true.

When MCNP encountered this case, it would effectively "fall off" the relevant portions of the data table and use nonsensical data. This issue was found in the (n,4n) reaction of Ac-226 in ENDF/B-VII.1 only because the data used resulted in a negative emission energy causing MCNP to abort. Investigations resulted in the discovery of the nature of this issue, and the fixes needed to address it.

4 Modifications to MCNP6

The offending behavior was caused by code in the acecas.F90 routine of MCNP, which was correspondingly modified by the MCNP Development Team to address this issue. First, the index ℓ was being decided solely on the value of the interpolation parameter r. The old behavior was to select $\ell = i + 1$ if

$$\xi_2 < r, \tag{7}$$

and $\ell = i$ otherwise. This is fine when the outgoing energy representation has no discrete lines, i.e., all continuum, or if by happenstance the probabilties of sampling the continua in i and $i + 1$ are equal.

Rather, it makes sense to weight the probability of sampling i or $i + 1$ by their relative probabilities. Define w_i as the probability of sampling the continuum at incident energy grid point i. The new behavior is to select $\ell = i + 1$ if

$$\xi_2 < \frac{r w_{i+1}}{r w_{i+1} + (1 - r) w_i}, \tag{8}$$

and $\ell = i$ otherwise. This not only is more mathematically reasonable from a probability theory point of view, but it also has the added effect that should a continuum not exist at incident energy grid point i, then, by definition $w_i = 0$, and MCNP will never try to sample data that do not exist.

To calculate E_f a unit-base interpolation still needs to be performed. Handling this depends on whether the emitted particle is a neutron or a photon. For neutrons, the interpolation factor r is set to one if the continuum on at i is absent and zero if the continuum at $i + 1$ is absent. In the photon case, the meaning of a zero continuum implies no photon emission. The convention is to use a distribution from 0 to 1 eV (well below the typical photon energy cutoff of 1 keV), and these are what are used to calculate E_b and E_t.

The modifications to the acecas.F90 routine are given in Appendix A.

5 Testing and Impact

Checking of the new routines in MCNP6 was done by following the code execution in the Totalview debugger. The input file that caused the problem (Appendix B) was used, and variable states were changed within Totalview to ensure every viable code path in the new routine was followed as expected. The results show expected behavior. The input file was then run with the modified MCNP6, and it ran to completion supporting the results of the direct checking of code execution.

There is no impact on the Regression tests or in results of the Validation Criticality tests. The extended test set was run, and only one out of the 900+ problems was found to be different. This was test problem 8 in MCNPX EXTENDED test27c. The difference appears in both the results and the output file. Analysis of the balance tables in the output file shows a small change in the photon average energy emitted as a result of neutron collisions, which is to be expected. The answers themselves changed by a relatively small amount. The differences of both the output and MCTAL files are in Appendix C.

The ENDF/B-VII.0 and ENDF/B-VII.1 data were queried to see if there are any other instances where continua are present in some parts of the table but not others. No such instances are in ENDF/B-VII.0. Several instances exist in ENDF/B-VII.1, but these are minor actinides and usually of small concern for most applications. A full list of isotopes with data that may cause erroneous sampling with older versions of MCNP is given in Appendix D.

6 Conclusions

The ENDF Law 4/44/61 sampling routines have been modified to account for the case where there is a mix of emission continua present and absent. The change in the sampling now includes a relative weighting by the probability of continuum emission, which is more consistent. Testing has shown that changes in results because of this are expected to be small.

Appendix A: acecas.F90 Code Differences

```
diff -r1.29 acecas.F90
66a67,68
>   real(DKND) :: e11, e12, e21, e22, w1, w2
179,180c181,194
<       t1 = xss(lc+nd+1) + r*(xss(ld+nd+1)-xss(lc+nd+1))
<       t2 = xss(lc+np) + r*(xss(ld+mp)-xss(lc+np))
---
>       ! select contiuum grid to use if discrete not found
>       ! use weighted average of continuum probabilities for
>       ! each side fo the grid
>       ! note: this could be done later, but is done here to preserve
>       !       random number usage for historical reasons.
>       if ( nd > 0 ) then
>         w1 = one - xss(lc + 2*np + nd)
>         w2 = one - xss(ld + 2*mp + nd)
>       else
>         w1 = one
>         w2 = one
>       endif
>
182c196
<       if ( ra < r ) then
---
>       if ( ra < r*w2/(r*w2 + (one-r)*w1) ) then
221a240,270
>     ! if continuum is absent from one side of the table, theni for
>     ! neutron use the side with the continuum. for photons, the data
>     ! means to sample zero photons, which is, by convention, signified
>     ! by a distribution from 0 to 1 eV. if both sides of the incident
>     ! energy lack a continuum then the code should not reach here.
>     if ( np > nd ) then
>       e11 = xss(lc+nd+1)
>       e12 = xss(lc+np)
>     else
>       ! continuum absent from left side of incident energy table.
>       e11 = zero
>       e12 = 1.d-6
>       if ( pbl%i%ipt == NEUTRON ) then
>         r = one
>       endif
>     endif
>     if ( mp > nd ) then
>       e21 = xss(ld+nd+1)
>       e22 = xss(ld+mp)
>     else
>       ! continuum absent from right side of incident energy table.
>       e21 = zero
>       e22 = 1.d-6
>       if ( pbl%i%ipt == NEUTRON ) then
>         r = zero
>       endif
>     endif
>     ! t1 and t2 are emin and emax for unit-base interpolated energy grid
>     t1 = e11 + r*(e21 - e11)
>     t2 = e12 + r*(e22 - e12)
```

Appendix B: Ac-226 Test Problem

```
Actinium-226 Sphere at the Origin
1 1 -10.07   -1   imp:n,p=1   $ Sphere of actinium-226 centered at the origin
2 0           1   imp:n,p=0

1 so 10

mode n p
nonu
m1  89226.83c    1.0          $ Actinium-226 at 1200 K
tmp 1.034100E-07 1.034100E-07
sdef pos=0 0 0 rad=d1 erg=d2
si1 0  10
sp1 -21  2
si2 a                      1.e-11 1.0202e-11 1.0408e-11 &
 1.0618e-11 1.0832e-11 1.1051e-11 1.1274e-11 1.1502e-11 &
 1.1735e-11 1.1972e-11 1.2214e-11 1.2460e-11 1.2712e-11 &
 1.2969e-11 1.3231e-11 1.3498e-11 1.3771e-11 1.4049e-11 &
 1.4333e-11 1.4622e-11 1.4918e-11 1.5219e-11 1.5527e-11 &
 1.5840e-11 1.6160e-11 1.6487e-11 1.6820e-11 1.7160e-11 &
 1.7506e-11 1.7860e-11 1.8221e-11 1.8589e-11 1.8964e-11 &
 1.9347e-11 1.9738e-11 2.0137e-11 2.0544e-11 2.0959e-11 &
 2.1382e-11 2.1814e-11 2.2255e-11 2.2704e-11 2.3163e-11 &
 2.3631e-11 2.4108e-11 2.4596e-11 2.5092e-11 2.5599e-11 &
 2.6116e-11 2.6644e-11 2.7182e-11 2.7731e-11 2.8292e-11 &
 2.8863e-11 2.9446e-11 3.0041e-11 3.0648e-11 3.1267e-11 &
 3.1899e-11 3.2543e-11 3.3201e-11 3.3871e-11 3.4556e-11 &
 3.5254e-11 3.5966e-11 3.6692e-11 3.7434e-11 3.8190e-11 &
 3.8961e-11 3.9749e-11 4.0551e-11 4.1371e-11 4.2206e-11 &
 4.3059e-11 4.3929e-11 4.4816e-11 4.5722e-11 4.6645e-11 &
 4.7588e-11 4.8549e-11 4.9530e-11 5.0530e-11 5.1551e-11 &
 5.2593e-11 5.3655e-11 5.4739e-11 5.5845e-11 5.6973e-11 &
 5.8124e-11 5.9298e-11 6.0496e-11 6.1718e-11 6.2965e-11 &
 6.4237e-11 6.5535e-11 6.6858e-11 6.8209e-11 6.9587e-11 &
 7.0993e-11 7.2427e-11 7.3890e-11 7.5383e-11 7.6906e-11 &
 7.8459e-11 8.0044e-11 8.1661e-11 8.3311e-11 8.4994e-11 &
 8.6711e-11 8.8463e-11 9.0250e-11 9.2073e-11 9.3933e-11 &
 9.5830e-11 9.7766e-11 9.9741e-11 1.0175e-10 1.0381e-10 &
 1.0590e-10 1.0804e-10 1.1023e-10 1.1245e-10 1.1473e-10 &
 1.1704e-10 1.1941e-10 1.2182e-10 1.2428e-10 1.2679e-10 &
 1.2935e-10 1.3197e-10 1.3463e-10 1.3735e-10 1.4013e-10 &
 1.4296e-10 1.4585e-10 1.4879e-10 1.5180e-10 1.5486e-10 &
 1.5799e-10 1.6119e-10 1.6444e-10 1.6776e-10 1.7115e-10 &
 1.7461e-10 1.7814e-10 1.8174e-10 1.8541e-10 1.8915e-10 &
 1.9297e-10 1.9687e-10 2.0085e-10 2.0491e-10 2.0905e-10 &
 2.1327e-10 2.1758e-10 2.2197e-10 2.2646e-10 2.3103e-10 &
 2.3570e-10 2.4046e-10 2.4532e-10 2.5028e-10 2.5533e-10 &
 2.6049e-10 2.6575e-10 2.7112e-10 2.7660e-10 2.8219e-10 &
 2.8789e-10 2.9370e-10 2.9964e-10 3.0569e-10 3.1186e-10 &
 3.1816e-10 3.2459e-10 3.3115e-10 3.3784e-10 3.4466e-10 &
 3.5163e-10 3.5873e-10 3.6598e-10 3.7337e-10 3.8091e-10 &
 3.8861e-10 3.9646e-10 4.0447e-10 4.1264e-10 4.2097e-10 &
 4.2948e-10 4.3816e-10 4.4701e-10 4.5604e-10 4.6525e-10 &
 4.7465e-10 4.8424e-10 4.9402e-10 5.0400e-10 5.1418e-10 &
 5.2457e-10 5.3517e-10 5.4598e-10 5.5701e-10 5.6826e-10 &
 5.7974e-10 5.9145e-10 6.0340e-10 6.1559e-10 6.2802e-10 &
 6.4071e-10 6.5365e-10 6.6686e-10 6.8033e-10 6.9407e-10 &
 7.0809e-10 7.2240e-10 7.3699e-10 7.5188e-10 7.6707e-10 &
 7.8257e-10 7.9838e-10 8.1450e-10 8.3096e-10 8.4774e-10 &
 8.6487e-10 8.8234e-10 9.0017e-10 9.1835e-10 9.3690e-10 &
 9.5583e-10 9.7514e-10 9.9484e-10 1.0149e-9 1.0354e-9 &
 1.0563e-9 1.0777e-9 1.0994e-9 1.1216e-9 1.1443e-9 &
 1.1674e-9 1.1910e-9 1.2151e-9 1.2396e-9 1.2646e-9 &
 1.2902e-9 1.3163e-9 1.3428e-9 1.3700e-9 1.3977e-9 &
 1.4259e-9 1.4547e-9 1.4841e-9 1.5141e-9 1.5447e-9 &
 1.5759e-9 1.6077e-9 1.6402e-9 1.6733e-9 1.7071e-9 &
 1.7416e-9 1.7768e-9 1.8127e-9 1.8493e-9 1.8867e-9 &
 1.9248e-9 1.9636e-9 2.0033e-9 2.0438e-9 2.0851e-9 &
 2.1272e-9 2.1702e-9 2.2140e-9 2.2587e-9 2.3044e-9 &
 2.3509e-9 2.3984e-9 2.4469e-9 2.4963e-9 2.5467e-9 &
 2.5982e-9 2.6507e-9 2.7042e-9 2.7588e-9 2.8146e-9 &
 2.8714e-9 2.9294e-9 2.9886e-9 3.0490e-9 3.1106e-9 &
 3.1734e-9 3.2375e-9 3.3029e-9 3.3697e-9 3.4377e-9 &
 3.5072e-9 3.5780e-9 3.6503e-9 3.7241e-9 3.7993e-9 &
 3.8761e-9 3.9544e-9 4.0342e-9 4.1157e-9 4.1989e-9 &
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 4.7342e-9 4.8299e-9 4.9274e-9 5.0270e-9 5.1285e-9 &
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 5.7824e-9 5.8992e-9 6.0184e-9 6.1400e-9 6.2640e-9 &
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 8.6264e-9 8.8006e-9 8.9784e-9 9.1598e-9 9.3448e-9 &
 9.5336e-9 9.7262e-9 9.9227e-9 1.0123e-8 1.0327e-8 &
 1.0536e-8 1.0749e-8 1.0966e-8 1.1187e-8 1.1413e-8 &
 1.1644e-8 1.1879e-8 1.2119e-8 1.2364e-8 1.2614e-8 &
 1.2869e-8 1.3129e-8 1.3394e-8 1.3664e-8 1.3940e-8 &
 1.4222e-8 1.4509e-8 1.4802e-8 1.5102e-8 1.5407e-8 &
 1.5718e-8 1.6035e-8 1.6359e-8 1.6690e-8 1.7027e-8 &
 1.7371e-8 1.7722e-8 1.8080e-8 1.8445e-8 1.8818e-8 &
 1.9198e-8 1.9586e-8 1.9981e-8 2.0385e-8 2.0797e-8 &
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8.5819e-7 8.7553e-7 8.9321e-7 9.1126e-7 9.2967e-7 &
9.4845e-7 9.6761e-7 9.8715e-7 1.0070e-6 1.0274e-6 &
1.0482e-6 1.0693e-6 1.0909e-6 1.1130e-6 1.1355e-6 &
1.1584e-6 1.1818e-6 1.2057e-6 1.2300e-6 1.2549e-6 &
1.2802e-6 1.3061e-6 1.3325e-6 1.3594e-6 1.3869e-6 &
1.4149e-6 1.4435e-6 1.4726e-6 1.5024e-6 1.5327e-6 &
1.5637e-6 1.5953e-6 1.6275e-6 1.6604e-6 1.6939e-6 &
1.7281e-6 1.7631e-6 1.7987e-6 1.8350e-6 1.8721e-6 &
1.9099e-6 1.9485e-6 1.9878e-6 2.0280e-6 2.0690e-6 &
2.1108e-6 2.1534e-6 2.1969e-6 2.2413e-6 2.2866e-6 &
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2.5781e-6 2.6302e-6 2.6833e-6 2.7375e-6 2.7928e-6 &
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3.3444e-1 3.2782e-1 3.2133e-1 3.1496e-1 3.0873e-1 &
3.0261e-1 2.9662e-1 2.9075e-1 2.8499e-1 2.7935e-1 &
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 3.3617e-3 3.2952e-3 3.2299e-3 3.1660e-3 3.1033e-3 &
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 2.7524e-3 2.6979e-3 2.6444e-3 2.5921e-3 2.5407e-3 &
 2.4904e-3 2.4411e-3 2.3928e-3 2.3454e-3 2.2990e-3 &
 2.2534e-3 2.2088e-3 2.1651e-3 2.1222e-3 2.0802e-3 &
 2.0390e-3 1.9986e-3 1.9590e-3 1.9202e-3 1.8822e-3 &
 1.8449e-3 1.8084e-3 1.7726e-3 1.7652e-3
c
nps   1
C
rand    gen=2   hist=187527252   seed=62924185359049
print
```

Appendix C: Differences in Test Problem

MCNPX_EXTENDED/test27c/difo08

```
2423c2423
<  from neutrons          414    4.7115E-02    3.3551E-02          compton scatter          0    0.            2.7034E-01
---
>  from neutrons          414    4.7115E-02    3.3602E-02          compton scatter          0    0.            2.7034E-01
2801c2801
<          1        1  20040.21c 3.33E-01         154  1.5395E-02  8.8795E-04  0.0000E+00  0.0000E+00          15  1.5638E-03  2.3804E+00
---
>          1        1  20040.21c 3.33E-01         154  1.5395E-02  8.8795E-04  0.0000E+00  0.0000E+00          15  1.5638E-03  2.4132E+00
2805c2805
<               total                             934  9.3309E-02  1.8618E-03  5.9691E-04  9.9641E-04         414  4.7115E-02  7.1211E-01
---
>               total                             934  9.3309E-02  1.8618E-03  5.9691E-04  9.9641E-04         414  4.7115E-02  7.1320E-01
2811c2811
<                    20040.21c                    154  1.5395E-02  8.8795E-04  0.0000E+00  0.0000E+00          15  1.5638E-03  2.3804E+00
---
>                    20040.21c                    154  1.5395E-02  8.8795E-04  0.0000E+00  0.0000E+00          15  1.5638E-03  2.4132E+00
2837c2837
<         1        1          414       4.71149E-02    3.35510E-02    7.12111E-01    4.21564E-01    5.01176E-01    3.56893E-01
---
>         1        1          414       4.71149E-02    3.36025E-02    7.13203E-01    4.22210E-01    5.01176E-01    3.57440E-01
2840c2840
<              total          414       4.71149E-02    3.35510E-02    7.12111E-01
---
>              total          414       4.71149E-02    3.36025E-02    7.13203E-01
4612c4612
<     2.0996E+00   7.00000E-04 0.3778
---
>     2.0996E+00   6.00000E-04 0.4081
4665c4665
<     2.6172E+00   6.00000E-04 0.4081
---
>     2.6172E+00   7.00000E-04 0.3778
7702c7702
<     2.0996E+00   2.60000E-03 0.1959
---
>     2.0996E+00   2.50000E-03 0.1997
7755c7755
<     2.6172E+00   1.40000E-03 0.2671
---
>     2.6172E+00   1.50000E-03 0.2580
8944c8944
<     2.2909E+00   4.89999E-03 0.1425
---
>     2.2909E+00   4.79999E-03 0.1440
8946c8946
<     2.7542E+00   2.28343E-02 0.0661
---
>     2.7542E+00   2.29343E-02 0.0659
9672c9672
<     2.2909E+00   8.16543E-02 0.0345
---
>     2.2909E+00   8.15543E-02 0.0345
9674c9674
<     2.7542E+00   3.06182E-01 0.0161
---
>     2.7542E+00   3.06282E-01 0.0161
```

MCNPX_EXTENDED/test27c/difm08

```
614c614
<   4.00000E-04 0.4999  5.00000E-04 0.4471  2.00000E-04 0.7070  7.00000E-04 0.3778
---
>   4.00000E-04 0.4999  5.00000E-04 0.4471  2.00000E-04 0.7070  6.00000E-04 0.4081
628c628
<   6.00000E-04 0.4081  1.00000E-04 0.9999  2.00000E-04 0.7070  6.00000E-04 0.4081
---
>   7.00000E-04 0.3778  1.00000E-04 0.9999  2.00000E-04 0.7070  6.00000E-04 0.4081
1384c1384
<   1.70000E-03 0.2423  2.60000E-03 0.1959  2.80000E-03 0.1887  2.90000E-03 0.1854
---
>   1.70000E-03 0.2423  2.50000E-03 0.1997  2.80000E-03 0.1887  2.90000E-03 0.1854
1397c1397
<   1.70000E-03 0.2562  1.30000E-03 0.2978  1.40000E-03 0.2671  1.00000E-03 0.3161
---
>   1.70000E-03 0.2562  1.30000E-03 0.2978  1.50000E-03 0.2580  1.00000E-03 0.3161
1695,1696c1695,1696
<   4.43331E-03 0.1506  3.90000E-03 0.1639  4.89999E-03 0.1425  4.10000E-03 0.1559
<   2.28343E-02 0.0661  1.21000E-02 0.0904  3.28000E-02 0.0545  5.61951E-03 0.1333
---
>   4.43331E-03 0.1506  3.90000E-03 0.1639  4.79999E-03 0.1440  4.10000E-03 0.1559
>   2.29343E-02 0.0659  1.21000E-02 0.0904  3.28000E-02 0.0545  5.61951E-03 0.1333
1864,1865c1864,1865
<   6.26187E-02 0.0398  5.84000E-02 0.0415  8.16543E-02 0.0345  4.78456E-02 0.0455
<   3.06182E-01 0.0161  1.53400E-01 0.0246  4.80419E-01 0.0118  7.91530E-02 0.0351
---
>   6.26187E-02 0.0398  5.84000E-02 0.0415  8.15543E-02 0.0345  4.78456E-02 0.0455
>   3.06282E-01 0.0161  1.53400E-01 0.0246  4.80419E-01 0.0118  7.91530E-02 0.0351
```

Appendix D: List of Affected Isotopes in ENDF/B-VII.1

Ac-226
Th-227
Th-228
Th-230
Th-233
Th-234
Pa-230
U-232
Np-235
Pu-242
Pu-246
Cm-243
Cm-245
Cm-247
Cm-248
Cm-249
Bk-246
Bk-248
Bk-249
Cf-246
Cf-250
Cf-251
Cf-252
Cf-253
Cf-254
Es-252
Es-253
Es-255