LLNL-TR-836050

^{252}Cf Spectrum Average Cross Sections and Spectral Indices Benchmarks

Dave Heinrichs
Ed Lent
Nuclear Criticality Safety Division

Lawrence Livermore National Laboratory, 7000 East Avenue, P.O. Box 808, L-198, Livermore, California, 94551, 0808, USA

Auspices

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

1.0 INTRODUCTION

The International Atomic Energy Agency (IAEA) Nuclear Data Section (NDS) has published results on-line[1] for their Coordinated Research Project (CRP Code F41031) focused on "Testing and Improving the IAEA International Reactor Dosimetry and Fusion File[2] (IRDFF), which includes a detailed summary paper[3] describing the lastest version of the library, IRDFF-II, and includes a compendium of measured ^{252}Cf spectrum average cross-sections.

This document includes the results of COG11.3 calculated ^{252}Cf spectrum average cross sections of interest to LLNL NCSD using IRDFF-II, IRDFF1.05, ENDF/B-VIII.0, ENDF/B-V and JEFF-3.3 nuclear data for comparison to reference values of Manojlovič, Mannhart, and Csikai as cited in the IAEA compendium[3] and a previous version[4] where necessary. Primary references as cited are provided in the Bibliography.

2.0 METHODOLOGY

^{252}Cf spectrum weighted cross-sections were calculated using COG11.3 with either IRDFF-II, IRDFF1.05, ENDF/B-VIII.0, ENDF/B-V or JEFF3.3 cross-sections. In all cases the IRDFF-II ^{252}Cf spectrum was used but truncated below 0.01 meV and above 20 MeV since the cross-section libraries do not generally extend to zero energy and often contain no data above 20 MeV. ^{252}Cf source neutrons were uniformly distributed within the volume of a sphere of arbitrary 90-cm radius, emitted isotropically, and transported through a vacuum where they cross another arbitrary 100-cm radius sphere used for detector scoring, and then continue on until they encounter a vacuum boundary on a sphere of 200-cm radius.

Two detectors are used to calculate a spectrum-average cross section. In all cases, a boundary-crossing detector (i.e., number=#0000001) is used to score the neutron number flux (<Φ>) averaged over all energies:

```
number=#0000001 title="Cf-252 SF-spectrum flux"
boundary 1 2 1.256637E+5 drf-e neutron number-flux
```

and another boundary-crossing detector is used to score a reaction rate (<RR>) of interest also averaged over all energies; e.g.:

```
number=#0000002 title="Cf-252 SF-spectrum averaged Pu-239(n,f) x-s"
boundary 1 2 1.256637E+5 drf-e neutron r-rate 1 15
```

Note that "r-rate 1 15" corresponds to reaction number 15 (i.e., fission) in material number 1, which in this case is Pu-239. The average cross-section is just the average reaction rate divided by the average flux, or <RR>/<Φ>. In this model, the particle transport occurs in just two regions (1 and 2) which are both assigned a vacuum. Therefore, the flux crossing the detector surface (between regions 1 and 2 of area 1.256637E+5 cm^2) corresponds to an uncollided "pure" ^{252}Cf spectrum. The reaction rate is simply this flux weighted by the reaction cross-section used as a detector response function, which in no way perturbs the flux. A complete COG11.3 input listing is provided in Appendix A.

Note that "r-rate" corresponds to a reaction number for a material specified using the nlib parameter in the MIX block; e.g., nlib=ENDFB8R0. This library corresponds to a complete library suitable for particle transport. COG11.3 also provides a doslib parameter; e.g., doslib=IRDFF-II. In this case "irdff-r-r" is used to specify reaction rates from an incomplete library of partial (dosimetry) reactions.

---

1 https://www-nds.iaea.org/IRDFF/

2 https://www.iaea.org/projects/crp/f41031

3 A. Trkov et al., "IRDFF-II: A New Neutron Metrology Library," Nuclear Data Sheets: **163** (2020) 1-108.

3.0 RESULTS

COG calculated results using the IRDFF-II ^{252}Cf spectrum and either the IRDFF-II, IRDFF1.05, ENDF/B-VIII.0, ENDF/B-V or JEFF3.3 cross-sections are provided in Tables 1-4 with a comparison to IAEA reference values. IRDFF results are also compared to calculated values by Trkov using MCNP[3,4]. The reactions of interest are those utilized in the LLNL Nuclear Accident Dosimeter[5] (NAD) design; namely:

- $^{32}S(n,p)^{23}P$
- $^{63}Cu(n,g)^{64}Cu$
- $^{115}In(n,ng)^{115m}In$
- $^{197}Au(n,g)^{198}Au$

Calculations were also performed for all the reactions used in the activation foils for the SILENE CAAS (ICSBEP) Benchmark[6]:

- $^{24}Mg(n,p)^{24}Na$
- $^{54}Fe(n,p)^{54}Mn$
- $^{56}Fe(n,p)^{56}Mn$
- $^{58}Ni(n,p)^{58}Co$
- $^{59}Co(n,g)^{60}Co$
- $^{115}In(n,g)^{116}In$
- $^{115}In(n,ng)^{115m}In$
- $^{197}Au(n,g)^{198}Au$

Calculations were also performed for fission foils commonly used at LLNL and NCERC; namely:

- $^{232}Th(n,g)$
- $^{232}Th(n,f)$
- $^{235}U(n,f)$
- $^{238}U(n,f)$
- $^{237}Np(n,f)$
- $^{239}Pu(n,f)$

3.1 RESULTS USING IRDFF CROSS-SECTIONS

Table 1 shows that the values calculated with COG11.3 using IRDFF-II data are in good agreement with reference values with a few exceptions:

The result for $^{59}Co(n,g)$ is poor since $|C/E - 1| >> 3\sigma$. Note that the C/E=0.699 value for COG11.3 is in agreement with the C/E=0.72 value calculated by FISPACT-II[7] using TENDL-2017.

---

4 INDC(NDS)-0616, *Summary Description of the New International Reactor Dosimetry and Fusion File (IRDFF release 1.0)*, Eva M. Zsolnay *et al*., May 2012.

5 LLNL-TR-489712, *Evaluation of LLNL's Nuclear Accident Dosimeters at the CALIBAN Reactor September 2010*, D. P. Hickman *et al*., June 24, 2011.

6 LLNL-CONF-680538, *COG Validation for Foil and TLD Irradiation in a SILENE Criticality Excursion Benchmark Experiment,* S. S. Kim *et al*., January 4, 2016.

7 UKAEA-R(18)004, "Integro-Differential Verification and Validation, FISPACT-II & TENDL-2017 nuclear data libraries," Michael Fleming *et al*., February 2018.

The result for ^{115}In(n,g) is also poor as |C/E – 1| >> 3σ. Surprisingly, IRDFF-II does not include the ^{115}In(n,ng) reaction, which is available in previous versions of the library and the result using IRDFF1.05 is included in the table and shown to produce good results.

COG11.3 calculated values using IRDFF-II (and IRDFF1.05 for ^{115} In(n,ng)) are in very good agreement with the MCNP calculations by Trkov using IRDFF-II (and IRDFF1.02 for ^{24}Mg(n,p) and ^{115}In(n,ng)).

Table 1. COG11.3/IRDFF calculated ^{252}Cf spectrum averaged cross sections

Reaction	<RR>/<Φ>	<σ>	Reference Value	Reference	C/E	Trkov
^{24}Mg(n,p)	$\frac{2.1332E{-}8 \pm 0.071\%}{1.0156E{-}5 \pm 0.002\%}$	2.100 mb ± 0.071 %	1.996 mb ± 2.4 %	Mannhart	1.052 ± 2.4%	1.055 ± 0.0302
^{32}S(n,p)	$\frac{7.5155E{-}7 \pm 0.015\%}{1.0156E{-}5 \pm 0.002\%}$	74.00 mb ± 0.015 %	72.54 mb ± 3.5 %	Mannhart	1.020 ± 3.5%	1.0203 ± 0.0435
^{54}Fe(n,p)	$\frac{8.7753E{-}7 \pm 0.017\%}{1.0156E{-}5 \pm 0.002\%}$	86.41 mb ± 0.017 %	86.84 mb ± 1.3 %	Mannhart	0.995 ± 1.3%	0.9955 ± 0.0343
^{56}Fe(n,p)	$\frac{1.4833E{-}8 \pm 0.055\%}{1.0156E{-}5 \pm 0.002\%}$	1.461 mb ± 0.055 %	1.465 mb ± 1.8 %	Mannhart	0.997 ± 1.8%	0.9984 ± 0.0347
^{58}Ni(n,p)	$\frac{1.1914E{-}6 \pm 0.015\%}{1.0156E{-}5 \pm 0.002\%}$	117.31 mb ± 0.015 %	117.50 mb ± 1.3 %	Mannhart	0.998 ± 1.3%	0.9984 ± 0.0229
^{59}Co(n,g)	$\frac{4.9450E{-}8 \pm 0.420\%}{1.0156E{-}5 \pm 0.002\%}$	4.87 mb ± 0.42 %	6.97 mb ± 4.88 %	Csikai	**0.699** ± 4.9%	N/A
^{63}Cu(n,g)	$\frac{1.0581E{-}7 \pm 0.099\%}{1.0156E{-}5 \pm 0.002\%}$	10.418 mb ± 0.099 %	10.3 mb ± 2.9 %	Manojlovič	1.012 ± 2.9%	1.0106 ± 0.0893
^{115}In(n,ng)	$\frac{1.9342E{-}6 \pm 0.008\%}{1.0157E{-}5 \pm 0.002\%}$	190.4 mb ± 0.008 %	197.4 mb ± 1.4 %	Mannhart	0.965 ± 1.4%	0.966 ± 0.0218
^{115}In(n,g)	$\frac{1.5564E{-}6 \pm 0.008\%}{1.0156E{-}5 \pm 0.002\%}$	153.25 mb ± 0.008 %	125.6 mb ± 2.1 %	Mannhart	**1.220** ± 2.1%	N/A
^{197}Au(n,g)	$\frac{7.6210E{-}7 \pm 0.037\%}{1.0156E{-}5 \pm 0.002\%}$	75.04 mb ± 0.037 %	75.5 mb ± 1.3 %	Manojlovič	0.994 ± 1.3%	0.9931 ± 0.0185
^{232}Th(n,g)	$\frac{9.1509E{-}7 \pm 0.026\%}{1.0156E{-}5 \pm 0.002\%}$	90.10 mb ± 0.026 %	87.0 mb ± 1.8 %	Manojlovič	1.036 ± 1.8%	1.0741 ± 0.0422
^{232}Th(n,f)	$\frac{8.4640E{-}7 \pm 0.010\%}{1.0156E{-}5 \pm 0.002\%}$	83.34 mb ± 0.010 %	84.55 mb ± 2.3 %	Csikai	0.986 ± 2.3%	0.9864 ± 0.0820
^{235}U(n,f)	$\frac{1.2458E{-}5 \pm 0.002\%}{1.0156E{-}5 \pm 0.002\%}$	1226.7 mb ± 0.002 %	1210.0 mb ± 1.2 %	Mannhart	1.014 ± 1.2%	1.0138 ± 0.0170
^{238}U(n,f)	$\frac{3.2654E{-}6 \pm 0.009\%}{1.0157E{-}5 \pm 0.002\%}$	321.5 mb ± 0.009 %	325.7 mb ± 1.6 %	Mannhart	0.987 ± 1.6%	0.9872 ± 0.0209
^{237}Np(n,f)	$\frac{1.3811E{-}5 \pm 0.004\%}{1.0156E{-}5 \pm 0.002\%}$	1359.9 mb ± 0.004 %	1361.0 mb ± 1.6 %	Mannhart	0.999 ± 1.6%	0.9991 ± 0.0233
^{239}Pu(n,f)	$\frac{1.8259E{-}5 \pm 0.002\%}{1.0156E{-}5 \pm 0.002\%}$	1797.9 mb ± 0.003 %	1812.0 mb ± 1.4 %	Mannhart	0.992 ± 1.4%	0.9922 ± 0.0185

Notes: Values in **RED** correspond to |C/E – 1| > 3σ. IRDFF-II used for all calculations except IRDFF1.05 used for ^{115} In(n,ng). Trkov C/E values are for MCNP with IRDFF-II cross-sections except IRDFF1.02 used for ^{24}Mg(n,p) and ^{115}In(n,ng).

3.2 RESULTS USING ENDF/B-VIII.0 CROSS-SECTIONS

Table 2 shows that the values calculated with COG11.3 using ENDF/B-VIII.0 are good with some exceptions. The results for ^{59}Co(n,g), ^{115}In(n,g), ^{115}In(n,ng) and ^{24}Mg(n,p) are poor and generally worse, or much worse, in comparison to IRDFF.

Table 2. COG11.3/ENDF/B-VIII.0 calculated and reference ^{252}Cf spectrum averaged cross sections

Reaction	<RR>/<Φ>	<σ>	Reference Value	Reference	C/E
^{24}Mg(n,p)	$\frac{2.3040E-8 \pm 0.068\%}{1.0157E-5 \pm 0.002\%}$	2.268 mb ± 0.068 %	1.996 mb ± 2.4 %	Mannhart	**1.136** ± 2.4%
^{32}S(n,p)	$\frac{7.6043E-7 \pm 0.015\%}{1.0157E-5 \pm 0.002\%}$	74.87 mb ± 0.015 %	72.54 mb ± 3.5 %	Mannhart	1.032 ± 3.5%
^{54}Fe(n,p)	$\frac{8.7796E-7 \pm 0.017\%}{1.0156E-5 \pm 0.002\%}$	86.45 mb ± 0.017 %	86.84 mb ± 1.3 %	Mannhart	0.995 ± 1.3%
^{56}Fe(n,p)	$\frac{1.4857E-8 \pm 0.055\%}{1.0156E-5 \pm 0.002\%}$	1.463 mb ± 0.055 %	1.465 mb ± 1.8 %	Mannhart	0.999 ± 1.8%
^{58}Ni(n,p)	$\frac{1.1820E-6 \pm 0.016\%}{1.0156E-5 \pm 0.002\%}$	116.38 mb ± 0.016 %	117.50 mb ± 1.3 %	Mannhart	0.991 ± 1.3%
^{59}Co(n,g)	$\frac{4.4964E-8 \pm 0.369\%}{1.0156E-5 \pm 0.002\%}$	4.43 mb ± 0.369 %	6.97 mb ± 4.88 %	Csikai	**0.635** ± 4.9%
^{63}Cu(n,g)	$\frac{1.0548E-7 \pm 0.112\%}{1.0156E-5 \pm 0.002\%}$	10.39 mb ± 0.112 %	10.3 mb ± 2.9 %	Manojlovič	1.008 ± 2.9%
^{115}In(n,ng)	$\frac{9.8663E-6 \pm 0.008\%}{1.0156E-5 \pm 0.002\%}$	971.47 mb ± 0.008 %	197.4 mb ± 1.4 %	Mannhart	**4.921** ± 1.4%
^{115}In(n,g)	$\frac{1.5925E-6 \pm 0.008\%}{1.0157E-5 \pm 0.002\%}$	156.79 mb ± 0.008 %	125.6 mb ± 2.1 %	Mannhart	**1.248** ± 2.1%
^{197}Au(n,g)	$\frac{7.6207E-7 \pm 0.036\%}{1.0157E-5 \pm 0.002\%}$	75.03 mb ± 0.036 %	75.5 mb ± 1.3 %	Manojlovič	0.994 ± 1.3%
^{232}Th(n,g)	$\frac{9.2765E-7 \pm 0.021\%}{1.0157E-5 \pm 0.002\%}$	91.33 mb ± 0.021 %	87.0 mb ± 1.8 %	Manojlovič	1.050 ± 1.8%
^{232}Th(n,f)	$\frac{8.0303E-7 \pm 0.010\%}{1.0156E-5 \pm 0.002\%}$	79.07 mb ± 0.010 %	84.55 mb ± 2.3 %	Csikai	0.935 ± 2.3%
^{235}U(n,f)	$\frac{1.2459E-5 \pm 0.002\%}{1.0157E-5 \pm 0.002\%}$	1226.6 mb ± 0.003 %	1210.0 mb ± 1.2 %	Mannhart	1.014 ± 1.2%
^{238}U(n,f)	$\frac{3.2648E-6 \pm 0.009\%}{1.0156E-5 \pm 0.002\%}$	321.47 mb ± 0.009 %	325.7 mb ± 1.6 %	Mannhart	0.987 ± 1.6%
^{237}Np(n,f)	$\frac{1.3796E-5 \pm 0.004\%}{1.0157E-5 \pm 0.002\%}$	1358.3 mb ± 0.004 %	1361.0 mb ± 1.6 %	Mannhart	0.998 ± 1.6%
^{239}Pu(n,f)	$\frac{1.8258E-5 \pm 0.002\%}{1.0156E-5 \pm 0.002\%}$	1797.8 mb ± 0.003 %	1812.0 mb ± 1.4 %	Mannhart	0.992 ± 1.4%

Notes: The values in **RED** correspond to |C/E - 1 > 3σ|.

3.3 RESULTS USING JEFF3.3 CROSS-SECTIONS

Table 3 shows that the values calculated with COG11.3 using JEFF3.3 cross-section data are good with the same exceptions as ENDF/B-VIII.0 with one additional poor result noted for ^{54}Fe(n,p).

Table 3. COG11.3/JEFF3.3 calculated and reference ^{252}Cf spectrum averaged cross sections

Reaction	<RR>/<Φ>	<σ>	Reference Value	Reference	C/E
^{24}Mg(n,p)	$\frac{2.3040E-8 \pm 0.068\%}{1.0157E-5 \pm 0.002\%}$	2.268 mb ± 0.068 %	1.996 mb ± 2.4 %	Mannhart	**1.136** ± 2.4%
^{32}S(n,p)	$\frac{7.4968E-7 \pm 0.015\%}{1.0156E-5 \pm 0.002\%}$	73.82 mb ± 0.015 %	72.54 mb ± 3.5 %	Mannhart	1.018 ± 3.5%
^{54}Fe(n,p)	$\frac{7.9574E-7 \pm 0.017\%}{1.0156E-5 \pm 0.002\%}$	78.35 mb ± 0.017 %	86.84 mb ± 1.3 %	Mannhart	**0.902** ± 1.3%
^{56}Fe(n,p)	$\frac{1.4564E-8 \pm 0.055\%}{1.0156E-5 \pm 0.002\%}$	1.434 mb ± 0.055 %	1.465 mb ± 1.8 %	Mannhart	0.979 ± 1.8%
^{58}Ni(n,p)	$\frac{1.1881E-6 \pm 0.015\%}{1.0156E-5 \pm 0.002\%}$	116.99 mb ± 0.015 %	117.50 mb ± 1.3 %	Mannhart	0.996 ± 1.3%
^{59}Co(n,g)	$\frac{4.9294E-8 \pm 0.321\%}{1.0156E-5 \pm 0.002\%}$	4.85 mb ± 0.321 %	6.97 mb ± 4.88 %	Csikai	**0.696** ± 4.9%
^{63}Cu(n,g)	$\frac{1.0575E-7 \pm 0.074\%}{1.0157E-5 \pm 0.002\%}$	10.41 mb ± 0.074 %	10.3 mb ± 2.9 %	Manojlovič	1.011 ± 2.9%
^{115}In(n,ng)	$\frac{1.0916E-5 \pm 0.008\%}{1.0157E-5 \pm 0.002\%}$	1074.7 mb ± 0.008 %	197.4 mb ± 1.4 %	Mannhart	**5.444** ± 1.4%
^{115}In(n,g)	$\frac{1.7010E-6 \pm 0.008\%}{1.0156E-5 \pm 0.002\%}$	167.5 mb ± 0.008 %	125.6 mb ± 2.1 %	Mannhart	**1.333** ± 2.1%
^{197}Au(n,g)	$\frac{7.6000E-7 \pm 0.034\%}{1.0156E-5 \pm 0.002\%}$	74.83 mb ± 0.034 %	75.5 mb ± 1.3 %	Manojlovič	0.991 ± 1.3%
^{232}Th(n,g)	$\frac{9.2752E-7 \pm 0.023\%}{1.0157E-5 \pm 0.002\%}$	91.32 mb ± 0.023 %	87.0 mb ± 1.8 %	Manojlovič	1.050 ± 1.8%
^{232}Th(n,f)	$\frac{8.0315E-7 \pm 0.010\%}{1.0156E-5 \pm 0.002\%}$	79.08 mb ± 0.010 %	84.55 mb ± 2.3 %	Csikai	0.935 ± 2.3%
^{235}U(n,f)	$\frac{1.2440E-5 \pm 0.002\%}{1.0156E-5 \pm 0.002\%}$	1224.9 mb ± 0.003 %	1210.0 mb ± 1.2 %	Mannhart	1.012 ± 1.2%
^{238}U(n,f)	$\frac{3.2248E-6 \pm 0.009\%}{1.0157E-5 \pm 0.002\%}$	317.5 mb ± 0.009 %	325.7 mb ± 1.6 %	Mannhart	0.975 ± 1.6%
^{237}Np(n,f)	$\frac{1.3796E-5 \pm 0.004\%}{1.0156E-5 \pm 0.002\%}$	1358.4 mb ± 0.004 %	1361.0 mb ± 1.6 %	Mannhart	0.998 ± 1.6%
^{239}Pu(n,f)	$\frac{1.8323E-5 \pm 0.002\%}{1.0156E-5 \pm 0.002\%}$	1804.2 mb ± 0.003 %	1812.0 mb ± 1.4 %	Mannhart	0.996 ± 1.4%

Notes: The values in **RED** correspond to |C/E - 1 > 3σ|.

3.4 RESULTS USING ENDF/B-V CROSS SECTIONS

It was noticed the NBS[8] calculated spectral indices for ^{59}Co(n,g) in ratio to ^{235}U(n,f) and ^{238}U(n,f) produced good results (op. cit., Table X-7(B5)). These calculations used the ENDF/B-V dosimetry library. While this special purpose library is not available with COG11.3, the ENDF/B-V general purpose library is available in ACE format as MCNP.50c. Table 4 shows an improved result for the COG11.3 calculated ^{59}Co(n,g) reaction.

Table 4. COG11.3/MCNP.50c calculated and reference ^{252}Cf spectrum averaged cross sections

Reaction	<RR>/<Φ>	<σ>	Reference Value	Reference	C/E
^{59}Co(n,g)	$\frac{6.2011E{-}8 \pm 0.398\%}{1.0157E{-}5 \pm 0.002\%}$	6.105 mb ± 0.398 %	6.97 mb ± 4.88 %	Csikai	0.876 ± 5.00%

3.5 RECOMMENDATIONS

Comparing calculated C/E values, the following libraries are recommended to produce the best values.

Table 5. Recommended Libraries for Dosimetry Reactions

Reaction	Library	Reaction	Library	Reaction	Library	Reaction	Library
^{24}Mg(n,p)	IRDFF-II	^{58}Ni(n,p)	IRDFF-II JEFF3.3 ENDFB8R0	^{115}In(n,g)	IRDFF-II	^{235}U(n,f)	IRDFF-II
^{32}S(n,p)	JEFF3.3 IRDFF-II ENDFB8R0	^{59}Co(n,g)	MCNP.50c	^{197}Au(n,g)	IRDFF-II ENDFB8R0 JEFF3.3	^{238}U(n,f)	IRDFF-II ENDFB8R0 JEFF3.3
^{54}Fe(n,p)	ENDFB8R0 IRDFF-II	^{63}Cu(n,g)	ENDFB8R0 IRDFF-II JEFF3.3	^{232}Th(n,g)	IRDFF-II ENDFB8R0	^{237}Np(n,f)	IRDFF-II ENDFB8R0 JEFF3.3
^{56}Fe(n,p)	ENDFB8R0 IRDFF-II	^{115}In(n,ng)	IRDFF1.05	^{232}Th(n,f)	IRDFF-II	^{239}Pu(n,f)	JEFF3.3 IRDFF-II ENDFB8R0

3.6 SPECTRAL INDICES

Selected cross section ratios (i.e., "spectral indices") are provided in Table 6. Note that circa 1985 NBS measured and calculated spectral indices are observed to be in good agreement with those calculated from the most up to date IAEA reference values. Table 6 provides the results of COG11.3 calculations using all libraries studied to produce the best results.

[8] NBSIR 85-3151, "Compendium of Benchmark Neutron Fields for Reactor Dosimetry," James A. Grundl, Charles, M. Eisenhauer, National Bureau of Standards, January 1986.

Table 6. Selected ^{252}Cf Spectral Indices

Cross Section Ratios	COG11.3/ IRDFF-II [c]	COG11.3/ ENDFB8R0 [c]	COG11.3/ JEFF3.3 [c]	IAEA Ref. Cross Section Ratios	NBSIR 85-3151 Meas.[a] Values	NBSIR 85-3151 Calc.[b] Values
Fission/^{238}U Fission						
^{239}Pu(n,f)/ ^{238}U(n,f)	5.592	5.592	5.683	5.563 ± 0.118	5.60 ± 0.07	5.71
^{235}U(n,f)/ ^{238}U(n,f)	3.816	3.816	3.858	3.715 ± 0.074	3.73 ± 0.04	3.941
^{237}Np(n,f)/ ^{238}U(n,f)	4.230	4.230	4.278	4.179 ± 0.094	4.19 ± 0.06	4.31
Fission/^{235}U Fission						
^{239}Pu(n,f)/ ^{235}U(n,f)	1.466	1.466	1.473	1.498 ± 0.028	1.50 ± 0.03	1.450
Capture/^{238}U Fission						
^{232}Th(n,g)/ ^{238}U(n,f)	0.280	0.284	0.288	0.267 ± 0.006	N/A	0.286
^{197}Au(n,g)/ ^{238}U(n,f)	0.233	0.233	0.235	0.232 ± 0.005	0.237 ± 0.007	0.2433
^{59}Co(n,g)/ ^{238}U(n,f)	0.019	0.019	0.019	0.021 ± 0.001	N/A	0.01923
Threshold/^{238}U Fission						
^{115}In(n,ng)/ ^{238}U(n,f)	0.592	0.592	0.600	0.606 ± 0.013	0.598 ± 0.017	0.580
^{58}Ni(n,p)/ ^{238}U(n,f)	0.365	0.362	0.368	0.361 ± 0.007	0.366 ± 0.008	0.363
^{54}Fe(n,p)/ ^{238}U(n,f)	0.269	0.269	0.272	0.266 ± 0.005	0.269 ± 0.008	0.2816
^{56}Fe(n,p)/ ^{238}U(n,f)	0.00454	0.00455	0.00452	0.0045 ± 0.0001	0.00445 ± 0.00014	0.004509

[a] Table X-11. [b] Table X-7(B5). [c] Except MCNP.50c for ^{59}Co(n,g) and IRDFF1.05 for ^{115}In(n,ng) in all calculations; and ENDFB8R0 for ^{54}Fe(n,p) in the JEFF3.3 calculations.

4.0 BIBLIOGRAPHY

J. Csikai, Z. Dezso, "Average cross sections for the Cf-252 neutron spectrum. II. (n,f) reactions," in VIIth Gaussig Symp., Nov 1977, Report ZFK-376, Rossendorf, pp. 44-46 (1978); EXFOR 30415.004.

W. Mannhart, "Response of Activation Reactions in the Neutron Field of 252Cf(s.f.),"IAEA Tech. Report Series No. 452, IAEA, Vienna (2006), pp. 30–45. Available online at https://www-nds.iaea.org/publications/tecdocs/sti-doc-010-452/.

S. Manojlovic, A. Trkov, "Nuclear Cross Section Measurement Analysis in the Californium-252 Spectrum with the Monte Carlo Method", Conf. Nuclear Energy for New Europe 2011, Ljubljana, Slovenia, contribution 307.

Appendix A

Sample COG11.3 Input Listing

```
IAEA-NDS-193: Cf-252 spontaneous fission spectrum averaged S-32(n,pg) cross-section
basic
  neutron EV                               $ No URRPT for S-32
source                                     $
  npart=1E+8                               $
  define position = 1 sphere 0 0 0 90      $ Arbitrary volume source
  define energy   = 1 neutron distribution $ IRDFF-II SFS98252 Spectrum
$ Energy     Spectrum                      $
  1.000000E-5 2.03300E-12
  1.015625E-5 2.04882E-12
  1.031250E-5 2.06452E-12
  .
  .                                        $ 3,670 lines
  .
  1.998438E+7 1.73176E-12
  1.999219E+7 1.72236E-12
  2.000000E+7 1.71300E-12
  define time     = 1 steady
  define angle    = 1 isotropic
  increment 1 position=1 energy=1 time=1 angle=1
mix nlib=JEFF3.3 ptlib=PT.JEFF3.3
  mat=1 bunches s32 1.0 $ S-32 @ 1 atom/b.cm
assign-m
   1 0 2 0
geometry
  sector 1 Dummy1 -1
  sector 2 Dummy2  1 -2
  boundary vacuum     2
surfaces
  1 sphere 100.
  2 sphere 200.
Detector
 number=#0000001 title="Cf-252 SF-spectrum flux"
   boundary 1 2 1.256637E+5 $ = area
   drf-e neutron number-flux`
 number=#0000002 title="Cf-252 SF-spectrum averaged S-32(n,pg) x-s"
   boundary 1 2 1.256637E+5 $ = area
   drf-e neutron r-rate 1 40
end
```