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Bramblett and Czirr Self-Shielded Fission Rates for ^{235}U Physical and Analytic Benchmark

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FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Auspices

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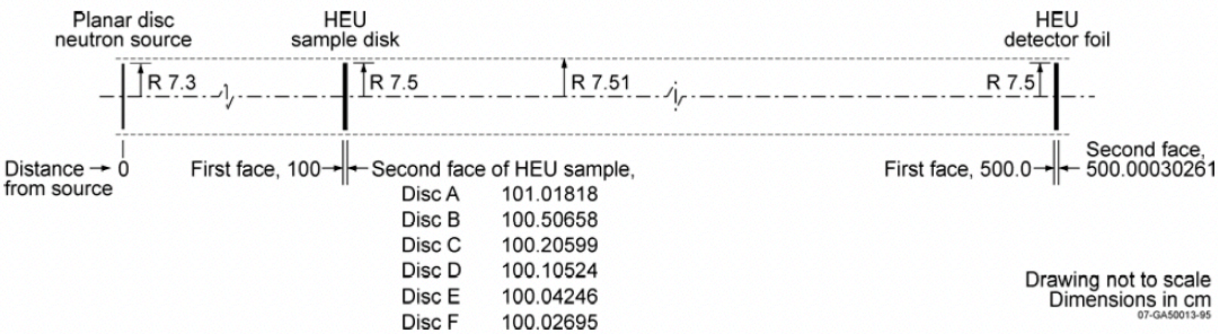
Introduction:

These experiments were performed by Bramblett and Czirr at UCRL (i.e., LLNL) in the late 1960s through the 1970s and evaluated by Mark Lee (LFO, retired) for the ICSBEP Handbook. Dimensions, geometry, and benchmark RSFR values are taken from the Handbook. All sample calculational results used COG 11.3 with ENDF/B-VIII.0 cross-sections. A sample input listing is provided in Appendix A.

Dimensions: Cylindrical symmetry about the x-axis

Modeled Surface	Distance from Source (cm)	Dimensions (cm)
Planar Disc Neutron Source	0 (origin)	diameter = 14.6
First face of HEU sample disc	100	diameter = 15
- Second face of HEU sample disc A	101.01818	diameter = 15
- Second face of HEU sample disc B	100.50658	diameter = 15
- Second face of HEU sample disc C	100.20599	diameter = 15
- Second face of HEU sample disc D	100.10524	diameter = 15
- Second face of HEU sample disc E	100.04246	diameter = 15
- Second face of HEU sample disc F	100.02695	diameter = 15
First face of HEU detector foil	500	diameter = 15
Second face of HEU detector foil	500.00030261	diameter = 15



Neutron source: 1/E spectrum from 0.359 eV to 2780 eV.

Note that the relative shielded fission rate (RSFR) experimental results extend from 0.464 eV to 2150 eV which are in the resolved resonance region since the unresolved resonance region extends from 2.25 keV to 25 keV according to L. C. Leal *et al.*, “An Unresolved Resonance Evaluation for ^{235}U,” in the PHYSOR 2004 proceedings.

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Materials: HEU sample discs (A-F) and detector foil

Table 12. Composition of HEU Sample Discs A and B (assumed density 18.7 g/cm^3).

Nuclide	Weight Fraction	Atom Density atoms/barn-cm
^{234}U	0.0136	6.544E-04
^{235}U	0.9322	4.466E-02
^{238}U	0.0542	2.564E-03

Table 13. Composition of HEU Sample Discs C and D (assumed density 18.7 g/cm^3).

Nuclide	Weight Fraction	Atom Density atoms/barn-cm
^{234}U	0.0129	6.207E-04
^{235}U	0.9313	4.462E-02
^{238}U	0.0558	2.640E-03

Table 14. Composition of HEU Sample Discs E and F (assumed density 18.7 g/cm^3).

Nuclide	Weight Fraction	Atom Density atoms/barn-cm
^{234}U	0.0114	5.485E-04
^{235}U	0.9317	4.464E-02
^{238}U	0.0569	2.692E-03

Table 15. Composition of HEU Detector Foil (assumed density 18.7 g/cm^3).

Nuclide	Weight Fraction	Atom Density atoms/barn-cm
^{234}U	0.012	5.774E-04
^{235}U	0.932	4.465E-02
^{238}U	0.056	2.694E-03

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Benchmark-Model and Sample Results: Sample A (19.04 g/cm^2)

Neutron Energy		COG11.3 with ENDF/B-VIII.0			Benchmark	
Group	Range (eV)	Sample Out*	Sample In**	RSFR	RSFR	C/E
1	0.464 – 1.0	8.819E–10 ± 0.0% 5.428E–04 ± 0.0% 1.875E–12 ± 0.0%	1.736E–11 ± 0.4% 1.073E–05 ± 0.4% 3.808E–14 ± 0.4%	0.020 ± 0.4%	0.028 ± 10.05%	0.71 ± 10.06%
2	1.0 – 2.15	9.509E–10 ± 0.0% 5.486E–04 ± 0.0% 2892E–12 ± 0.0%	1.262E–10 ± 0.1% 4.080E–05 ± 0.1% 4.026E–13 ± 0.1%	0.074 ± 0.1%	0.072 ± 10.06%	1.03 ± 10.06%
3	2.15 – 4.64	3.426E–09 ± 0.0% 6.075E–04 ± 0.0% 5.167E–12 ± 0.0%	1.179E–09 ± 0.2% 7.914E–05 ± 0.1% 1.437E–12 ± 0.1%	0.130 ± 0.1%	0.138 ± 10.01%	0.94 ± 10.0%
4	4.64 – 10.0	2.858E–07± 0.1% 3.406E–03 ± 0.0% 2.819E–10 ± 0.1%	4.764E–09 ± 0.2% 9.190E–05 ± 0.1% 2.743E–12 ± 0.2%	0.027 ± 0.1%	0.025 ± 15.04%	1.08 ± 15.04%
5	10.0 – 21.5	1.990E–10 ± 0.0% 4.137E–03 ± 0.0% 8.582E–10 ± 0.2%	2.940E–11 ± 0.1% 1.682E–04 ± 0.1% 4.040E–12 ± 0.2%	0.041 ± 0.1%	0.034 ± 6.11%	1.20 ± 6.11%
6	21.5 – 46.4	1.052E–09 ± 3.2% 6.564E–04 ± 0.1% 1.064E–11 ± 0.4%	9.866E–11 ± 1.0% 2.786E–05 ± 0.2% 1.344E–12 ± 0.1%	0.042 ± 0.2%	0.043 ± 5.41%	0.99 ± 5.41%
7	46.4 – 100	7.981E–10 ± 0.7% 1.573E–04 ± 0.1% 1.001E–11 ± 0.6%	2.778E–11 ± 2.0% 9.491E–06 ± 0.2% 3.579E–13 ± 1.2%	0.060 ± 0.2%	0.067 ± 5.81%	0.90 ± 5.81%
8	100 – 215	5.153E–09 ± 0.5% 9.394E–05 ± 0.1% 4.452E–12 ± 0.5%	9.098E–10 ± 1.3% 9.340E–06 ± 0.3% 1.799E–13 ± 1.6%	0.099 ± 0.3%	0.099 ± 5.50%	1.00 ± 5.51%
9	215 – 464	4.589E–09± 0.6% 7.509E–05 ± 0.1% 4.449E–12 ± 0.7%	1.484E–09 ± 1.3% 1.110E–05 ± 0.2% 3.698E–13 ± 2.3%	0.148 ± 0.2%	0.159 ± 2.82%	0.93 ± 2.83%
10	464 – 1000	1.239E–08 ± 0.4% 5.068E–05 ± 0.1% 3.603E–10 ± 1.1%	3.701E–09 ± 0.7% 1.088E–05 ± 0.2% 9.982E–11 ± 2.1%	0.215 ± 0.2%	0.214 ± 3.70%	1.00 ± 3.71%
11	1000 – 2150	5.701E–10 ± 0.3% 3.131E–05 ± 0.1% 1.228E–10 ± 1.3%	2.039E–10 ± 0.5% 9.474E–06 ± 0.1% 5.153E–11 ± 2.2%	0.303 ± 0.1%	0.302 ± 2.21%	1.00 ± 2.21%

*File: czirr-0. **File: czirr-a.

FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Benchmark-Model and Sample Results: Sample B (9.473 g/cm^2)

Neutron Energy		COG11.3 with ENDF/B-VIII.0			Benchmark	
Group	Range (eV)	Sample Out*	Sample In**	RSFR	RSFR	C/E
1	0.464 – 1.0	8.819E–10 ± 0.0% 5.428E–04 ± 0.0% 1.875E–12 ± 0.0%	7.486E–05 ± 0.1%	0.138 ± 0.1%	0.152 ± 5.01%	0.91 ± 5.01%
2	1.0 – 2.15	9.509E–10 ± 0.0% 5.486E–04 ± 0.0% 2.892E–12 ± 0.0%	1.129E–04 ± 0.1%	0.206 ± 0.1%	0.199 ± 5.08%	1.03 ± 5.08%
3	2.15 – 4.64	3.426E–09 ± 0.0% 6.075E–04 ± 0.0% 5.167E–12 ± 0.0%	1.828E–04 ± 0.1%	0.301 ± 0.1%	0.286 ± 6.71%	1.05 ± 6.71%
4	4.64 – 10.0	2.858E–07± 0.1% 3.406E–03 ± 0.0% 2.819E–10 ± 0.1%	2.606E–04 ± 0.1%	0.077 ± 0.1%	0.070 ± 7.55%	1.09 ± 7.55%
5	10.0 – 21.5	1.990E–10 ± 0.0% 4.137E–03 ± 0.0% 8.582E–10 ± 0.2%	4.828E–04 ± 0.0%	0.117 ± 0.0%	0.103 ± 6.11%	1.13 ± 6.11%
6	21.5 – 46.4	1.052E–09 ± 3.2% 6.564E–04 ± 0.1% 1.064E–11 ± 0.4%	9.078E–05 ± 0.1%	0.138 ± 0.1%	0.131 ± 4.60%	1.06 ± 4.60%
7	46.4 – 100	7.981E–10 ± 0.7% 1.573E–04 ± 0.1% 1.001E–11 ± 0.6%	2.692E–05 ± 0.2%	0.171 ± 0.2%	0.183 ± 5.82%	0.94 ± 5.82%
8	100 – 215	5.153E–09 ± 0.5% 9.394E–05 ± 0.1% 4.452E–12 ± 0.5%	2.389E–05 ± 0.2%	0.254 ± 0.2%	0.260 ± 5.50%	0.98 ± 5.50%
9	215 – 464	4.589E–09± 0.6% 7.509E–05 ± 0.1% 4.449E–12 ± 0.7%	2.545E–05 ± 0.1%	0.339 ± 0.1%	0.336± 2.81%	1.01 ± 2.81%
10	464 – 1000	1.239E–08 ± 0.4% 5.068E–05 ± 0.1% 3.603E–10 ± 1.1%	2.244E–05 ± 0.1%	0.443 ± 0.1%	0.440 ± 3.70%	1.01 ± 3.70%
11	1000 – 2150	5.701E–10 ± 0.3% 3.131E–05 ± 0.1% 1.228E–10 ± 1.3%	1.700E–05 ± 0.1%	0.543 ± 0.1%	0.542 ± 2.21%	1.00 ± 2.21%

*File: czirr-0. **File: czirr-b.

FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Benchmark-Model and Sample Results: Sample C (3.852 g/cm^2)

Neutron Energy		COG11.3 with ENDF/B-VIII.0			Benchmark	
Group	Range (eV)	Sample Out*	Sample In**	RSFR	RSFR	C/E
1	0.464 – 1.0	8.819E–10 ± 0.0% 5.428E–04 ± 0.0% 1.875E–12 ± 0.0%	2.411E–04 ± 0.1%	0.444 ± 0.1%	0.462 ± 2.01%	0.96 ± 2.01%
2	1.0 – 2.15	9.509E–10 ± 0.0% 5.486E–04 ± 0.0% 2.892E–12 ± 0.0%	2.587E–04 ± 0.1%	0.472 ± 0.1%	0.453 ± 2.03%	1.04 ± 2.03%
3	2.15 – 4.64	3.426E–09 ± 0.0% 6.075E–04 ± 0.0% 5.167E–12 ± 0.0%	3.438E–04 ± 0.0%	0.566 ± 0.0%	0.527 ± 6.70%	1.07 ± 6.70%
4	4.64 – 10.0	2.858E–07± 0.1% 3.406E–03 ± 0.0% 2.819E–10 ± 0.1%	6.545E–04 ± 0.0%	0.192 ± 0.0%	0.179 ± 6.51%	1.07 ± 6.51%
5	10.0 – 21.5	1.990E–10 ± 0.0% 4.137E–03 ± 0.0% 8.582E–10 ± 0.2%	1.107E–03 ± 0.0%	0.268 ± 0.0%	0.233 ± 6.10%	1.15 ± 6.10%
6	21.5 – 46.4	1.052E–09 ± 3.2% 6.564E–04 ± 0.1% 1.064E–11 ± 0.4%	2.383E–04 ± 0.1%	0.363 ± 0.1%	0.324 ± 4.60%	1.12 ± 4.60%
7	46.4 – 100	7.981E–10 ± 0.7% 1.573E–04 ± 0.1% 1.001E–11 ± 0.6%	6.445E–05 ± 0.2%	0.410 ± 0.2%	0.420 ± 5.80%	0.98 ± 5.80%
8	100 – 215	5.153E–09 ± 0.5% 9.394E–05 ± 0.1% 4.452E–12 ± 0.5%	4.893E–05 ± 0.1%	0.520 ± 0.1%	0.524 ± 5.50%	0.99 ± 5.50%
9	215 – 464	4.589E–09± 0.6% 7.509E–05 ± 0.1% 4.449E–12 ± 0.7%	4.597E–05 ± 0.1%	0.612 ± 0.1%	0.613± 2.80%	1.00 ± 2.80%
10	464 – 1000	1.239E–08 ± 0.4% 5.068E–05 ± 0.1% 3.603E–10 ± 1.1%	3.585E–05 ± 0.1%	0.707 ± 0.1%	0.703 ± 3.71%	1.01 ± 3.71%
11	1000 – 2150	5.701E–10 ± 0.3% 3.131E–05 ± 0.1% 1.228E–10 ± 1.3%	2.426E–05 ± 0.1%	0.775 ± 0.1%	0.773 ± 2.20%	1.00 ± 2.20%

*File: czirr-0. **File: czirr-c.

FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Benchmark-Model and Sample Results: Sample D (1.968 g/cm^2)

1.12 ± 6.10%Neutron Energy		COG11.3 with ENDF/B-VIII.0			Benchmark	
Group	Range (eV)	Sample Out*	Sample In**	RSFR	RSFR	C/E
1	0.464 – 1.0	8.819E–10 ± 0.0% 5.428E–04 ± 0.0% 1.875E–12 ± 0.0%	3.579E–04 ± 0.1%	0.659 ± 0.1%	0.662 ± 2.01%	1.00 ± 2.01%
2	1.0 – 2.15	9.509E–10 ± 0.0% 5.486E–04 ± 0.0% 2.892E–12 ± 0.0%	3.657E–04 ± 0.1%	0.667 ± 0.1%	0.672 ± 2.02%	0.99 ± 2.02%
3	2.15 – 4.64	3.426E–09 ± 0.0% 6.075E–04 ± 0.0% 5.167E–12 ± 0.0%	4.455E–04 ± 0.0%	0.733 ± 0.0%	0.719 ± 4.00%	1.02 ± 4.00%
4	4.64 – 10.0	2.858E–07± 0.1% 3.406E–03 ± 0.0% 2.819E–10 ± 0.1%	1.068E–03± 0.0%	0.314 ± 0.0%	0.297 ± 6.51%	1.06 ± 6.51%
5	10.0 – 21.5	1.990E–10 ± 0.0% 4.137E–03 ± 0.0% 8.582E–10 ± 0.2%	1.625E–03 ± 0.0%	0.393 ± 0.0%	0.352 ± 6.10%	1.12 ± 6.10%
6	21.5 – 46.4	1.052E–09 ± 3.2% 6.564E–04 ± 0.1% 1.064E–11 ± 0.4%	3.657E–04 ± 0.1%	0.557 ± 0.1%	0.477 ± 4.61%	1.17 ± 4.61%
7	46.4 – 100	7.981E–10 ± 0.7% 1.573E–04 ± 0.1% 1.001E–11 ± 0.6%	9.476E–05 ± 0.1%	0.602 ± 0.1%	0.605 ± 5.81%	1.00 ± 5.81%
8	100 – 215	5.153E–09 ± 0.5% 9.394E–05 ± 0.1% 4.452E–12 ± 0.5%	6.565E–05 ± 0.1%	0.699 ± 0.1%	0.719 ± 5.50%	0.97 ± 5.50%
9	215 – 464	4.589E–09± 0.6% 7.509E–05 ± 0.1% 4.449E–12 ± 0.7%	5.770E–05 ± 0.1%	0.768 ± 0.1%	0.780± 2.80%	0.99 ± 2.80%
10	464 – 1000	1.239E–08 ± 0.4% 5.068E–05 ± 0.1% 3.603E–10 ± 1.1%	4.228E–05 ± 0.1%	0.834 ± 0.1%	0.841 ± 3.71%	0.99 ± 3.71%
11	1000 – 2150	5.701E–10 ± 0.3% 3.131E–05 ± 0.1% 1.228E–10 ± 1.3%	2.754E–05 ± 0.1%	0.880 ± 0.1%	0.847 ± 2.20%	1.04 ± 2.20%

*File: czirr-0. **File: czirr-d.

FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Benchmark-Model and Sample Results: Sample E (0.794 g/cm^2)

1.12 ± 6.10%Neutron Energy		COG11.3 with ENDF/B-VIII.0			Benchmark	
Group	Range (eV)	Sample Out*	Sample In**	RSFR	RSFR	C/E
1	0.464 – 1.0	8.819E–10 ± 0.0% 5.428E–04 ± 0.0% 1.875E–12 ± 0.0%	4.585–04 ± 0.1%	0.845 ± 0.1%	0.848 ± 2.01%	1.00 ± 2.01%
2	1.0 – 2.15	9.509E–10 ± 0.0% 5.486E–04 ± 0.0% 2.892E–12 ± 0.0%	4.625–04 ± 0.1%	0.843 ± 0.1%	0.840 ± 2.01%	1.00 ± 2.01%
3	2.15 – 4.64	3.426E–09 ± 0.0% 6.075E–04 ± 0.0% 5.167E–12 ± 0.0%	5.334–04 ± 0.0%	0.878 ± 0.0%	0.874 ± 4.00%	1.00 ± 4.00%
4	4.64 – 10.0	2.858E–07± 0.1% 3.406E–03 ± 0.0% 2.819E–10 ± 0.1%	1.784–03 ± 0.0%	0.524 ± 0.0%	0.514 ± 6.52%	1.02 ± 6.52%
5	10.0 – 21.5	1.990E–10 ± 0.0% 4.137E–03 ± 0.0% 8.582E–10 ± 0.2%	2.399–03 ± 0.0%	0.580 ± 0.0%	0.524 ± 6.11%	1.11 ± 6.11%
6	21.5 – 46.4	1.052E–09 ± 3.2% 6.564E–04 ± 0.1% 1.064E–11 ± 0.4%	5.055–04 ± 0.1%	0.770 ± 0.1%	0.693 ± 4.61%	1.11 ± 4.61%
7	46.4 – 100	7.981E–10 ± 0.7% 1.573E–04 ± 0.1% 1.001E–11 ± 0.6%	1.265–04 ± 0.1%	0.804 ± 0.1%	0.785 ± 5.80%	1.02 ± 5.80%
8	100 – 215	5.153E–09 ± 0.5% 9.394E–05 ± 0.1% 4.452E–12 ± 0.5%	8.075–05 ± 0.1%	0.860 ± 0.1%	0.867 ± 5.50%	0.99 ± 5.50%
9	215 – 464	4.589E–09± 0.6% 7.509E–05 ± 0.1% 4.449E–12 ± 0.7%	6.725–05 ± 0.1%	0.896 ± 0.1%	0.894± 2.80%	1.00 ± 2.80%
10	464 – 1000	1.239E–08 ± 0.4% 5.068E–05 ± 0.1% 3.603E–10 ± 1.1%	4.708–05 ± 0.1%	0.929 ± 0.1%	0.932 ± 3.70%	1.00 ± 3.70%
11	1000 – 2150	5.701E–10 ± 0.3% 3.131E–05 ± 0.1% 1.228E–10 ± 1.3%	2.973–05 ± 0.1%	0.950 ± 0.1%	0.919 ± 2.20%	1.03 ± 2.20%

*File: czirr-0. **File: czirr-e.

FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Benchmark-Model and Sample Results: Sample F (0.504 g/cm^2)

1.12 ± 6.10%Neutron Energy		COG11.3 with ENDF/B-VIII.0			Benchmark	
Group	Range (eV)	Sample Out*	Sample In**	RSFR	RSFR	C/E
1	0.464 – 1.0	8.819E–10 ± 0.0% 5.428E–04 ± 0.0% 1.875E–12 ± 0.0%	4.877E–04 ± 0.1%	0.898 ± 0.1%	0.880 ± 2.01%	1.02 ± 2.01%
2	1.0 – 2.15	9.509E–10 ± 0.0% 5.486E–04 ± 0.0% 2.892E–12 ± 0.0%	4.920E–04 ± 0.1%	0.897 ± 0.1%	0.898 ± 2.01%	1.00 ± 2.01%
3	2.15 – 4.64	3.426E–09 ± 0.0% 6.075E–04 ± 0.0% 5.167E–12 ± 0.0%	5.586E–04 ± 0.0%	0.920 ± 0.0%	0.924 ± 2.01%	1.00 ± 2.01%
4	4.64 – 10.0	2.858E–07± 0.1% 3.406E–03 ± 0.0% 2.819E–10 ± 0.1%	2.165E–03 ± 0.0%	0.636 ± 0.0%	0.631± 2.05%	1.01 ± 2.05%
5	10.0 – 21.5	1.990E–10 ± 0.0% 4.137E–03 ± 0.0% 8.582E–10 ± 0.2%	2.803E–03± 0.0%	0.678 ± 0.0%	0.640± 2.05%	1.06 ± 2.05%
6	21.5 – 46.4	1.052E–09 ± 3.2% 6.564E–04 ± 0.1% 1.064E–11 ± 0.4%	5.531E–04 ± 0.1%	0.843 ± 0.1%	0.793 ± 2.03%	1.06 ± 2.03%
7	46.4 – 100	7.981E–10 ± 0.7% 1.573E–04 ± 0.1% 1.001E–11 ± 0.6%	1.364E–04 ± 0.1%	0.867 ± 0.1%	0.865 ± 2.02%	1.00 ± 2.02%
8	100 – 215	5.153E–09 ± 0.5% 9.394E–05 ± 0.1% 4.452E–12 ± 0.5%	8.504E–05 ± 0.1%	0.905 ± 0.1%	0.898 ± 2.01%	1.01 ± 2.01%
9	215 – 464	4.589E–09± 0.6% 7.509E–05 ± 0.1% 4.449E–12 ± 0.7%	7.003E–05 ± 0.1%	0.933 ± 0.1%	0.941± 2.01%	0.99 ± 2.01%
10	464 – 1000	1.239E–08 ± 0.4% 5.068E–05 ± 0.1% 3.603E–10 ± 1.1%	4.845E–05 ± 0.1%	0.956 ± 0.1%	0.939 ± 2.04%	1.02 ± 2.04%
11	1000 – 2150	5.701E–10 ± 0.3% 3.131E–05 ± 0.1% 1.228E–10 ± 1.3%	3.031E–05± 0.1%	0.968 ± 0.1%	0.938 ± 2.01%	1.03 ± 2.01%

*File: czirr-0. **File: czirr-f.

FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for ^{235}U

Conclusions:

While there are ^{234}U and ^{238}U fissions in the detector, they are negligible in comparison to ^{235}U fissions as shown in the tables for the results with the sample out. Therefore, only ^{235}U fissions are reported in other table entries.

The bias in calculated results is given in the table below using the bias statistic, $x = (C/E - 1)/\sigma$. These results are noted as excellent and in good agreement with a normal distribution with a slight positive mean bias. It may be that there is increasing under-prediction with increasing sample thickness but there are too few samples to make such a conclusion definitive.

Table 1. Bias statistic, $x = (C/E - 1)/\sigma$

Sample	$x < -3$	$-3 \le x < -2$	$-2 \le x < -1$	$-1 \le x < 0$	$0 \le x \le 1$	$1 < x \le 2$	$2 < x \le 3$	$3 < x \le 4$
A		1	1	2	5		1	1
B			2	1	5	2	1	
C			1	2	3	3	2	
D				4	4	2		1
E				1	7	2	1	
F				1	7	1	2	
All		1	4	11	31	10	7	2

This shift to increasing under-prediction with increasing sample thickness may also seen in the bias statistic, $y = C/E$, shown in the following table. Further, increasing uncertainties with increasing sample thickness are evident.

Table 2. Statistic, $y = C/E$

Sample	C/E	Uncertainty (%)
A	0.71 – 1.20	2.21 – 10.06
B	0.91 – 1.13	2.21 – 7.55
C	0.96 – 1.15	2.01 – 6.70
D	0.97 – 1.17	2.01 – 6.51
E	0.99 – 1.11	2.01 – 6.52
F	0.99 – 1.06	2.01 – 2.05
All	0.71 – 1.20	2.01 – 10.06

Bramblett and Czirr (1969) state: “In the geometry used in this experiment, a neutron scattered by the absorber will not strike the detector.” This appears to be rigorously true as shown by comparing the results with no sample present to those with the thinnest samples present. With the thickest samples, we note increased scattering and multiplication. However, even with these few scattering events only some of which are inelastic, the spectrum is expected to be substantially unaltered. This benchmark is therefore also a valuable analytic benchmark as discussed further in Appendix B.

Table 3. Total Response as a Function of Scattering Events Since Source Generation and Multiplication (M)

Sample	Percentage of Response as a Function of Scattering Events				M
	0	1	2	3+	
None	4.86	95.00	0.14		1.001
F	5.13	94.67	0.20		1.107
E	4.97	94.45	0.58		1.157
D	4.92	94.38	0.69	0.01	1.325
C	4.93	94.53	0.47	0.07	1.531
B	6.73	90.46	1.96	0.85	1.942
A	8.22	78.82	7.52	0.95	2.356

Note that k-eff can be calculated as the ratio of the production rate (P) to the removal rate (R), or k-eff = P/R. Therefore, M = 1/(1 – k-eff) = 1/(1 – P/R).

References

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Appendix A

Sample COG 11.3 Input Deck

```
FUND-LLNL-1/E-U235-TRANS-001, Self-Shielded Fission Rates for 235U: Sample F In
basic
  neutron delayedn MEV URRPT
source
  npart=1E+8                                         $
  define position = 1 ss-disk 0 0 0 5 0 0 7.3         $ 7.3 cm radius disk source at x=0
  define angle    = 1 normal fixed                    $ uniform normal along +x axis
  define energy   = 1 neutron one/e 3.590E-7 2.780E-3  $ 1/E spectrum
  define time     = 1 steady                          $
  increment 1 position=1 angle=1 energy=1 time=1
mix nlib=ENDFB8R0 ptlib=PT.ENDFB8R0.ACE
   mat=1 w-p 18.7 u234 0.0114 u235 0.9317 u238 0.0569  $ Sample F
   mat=2 w-p 18.7 u234 0.012  u235 0.932  u238 0.056   $ Fission chamber detector foil
   mat=24 u234  0.2244                                 $ For U-234 fissions in the detector
   mat=25 u235 17.4284                                 $ For U-235 fissions in the detector
   mat=28 u238  1.0472                                 $ For U-238 fissions in the detector
assign-mc
   1 red 2 blue
geometry
  sector 1 Sample  -1
  sector 2 DetFoil -2
  boundary vacuum   3
picture cs material -10 0 10 -10 0 -10 510 0 -10 title="axial view"
surfaces
  1 c x 7.5 100.0 100.02695    $ Sample F
  2 c x 7.5 500.0 500.00030261 $ Fission chamber detector foil
  3 c x 8.0 -10.0 510.0        $ Boundary condition
detector
number = U234 title="U234 Fissions in Fission Chamber" reaction 2 5.347560E-2 DRF-E neutron R-RATE 24 15
  bin E neutron 4.64e-7 1e-6 2.15e-6 4.64e-6 1.e-5 2.15e-5 4.64e-5 1e-4 2.15e-4 4.64e-4 1e-3 2.15e-3
number = U235 title="U235 Fissions in Fission Chamber" reaction 2 5.347560E-2 DRF-E neutron R-RATE 25 15
  bin E neutron 4.64e-7 1e-6 2.15e-6 4.64e-6 1.e-5 2.15e-5 4.64e-5 1e-4 2.15e-4 4.64e-4 1e-3 2.15e-3
number = U238 title="U238 Fissions in Fission Chamber" reaction 2 5.347560E-2 DRF-E neutron R-RATE 28 15
  bin E neutron 4.64e-7 1e-6 2.15e-6 4.64e-6 1.e-5 2.15e-5 4.64e-5 1e-4 2.15e-4 4.64e-4 1e-3 2.15e-3
end
```

Appendix B

Analytic Benchmark

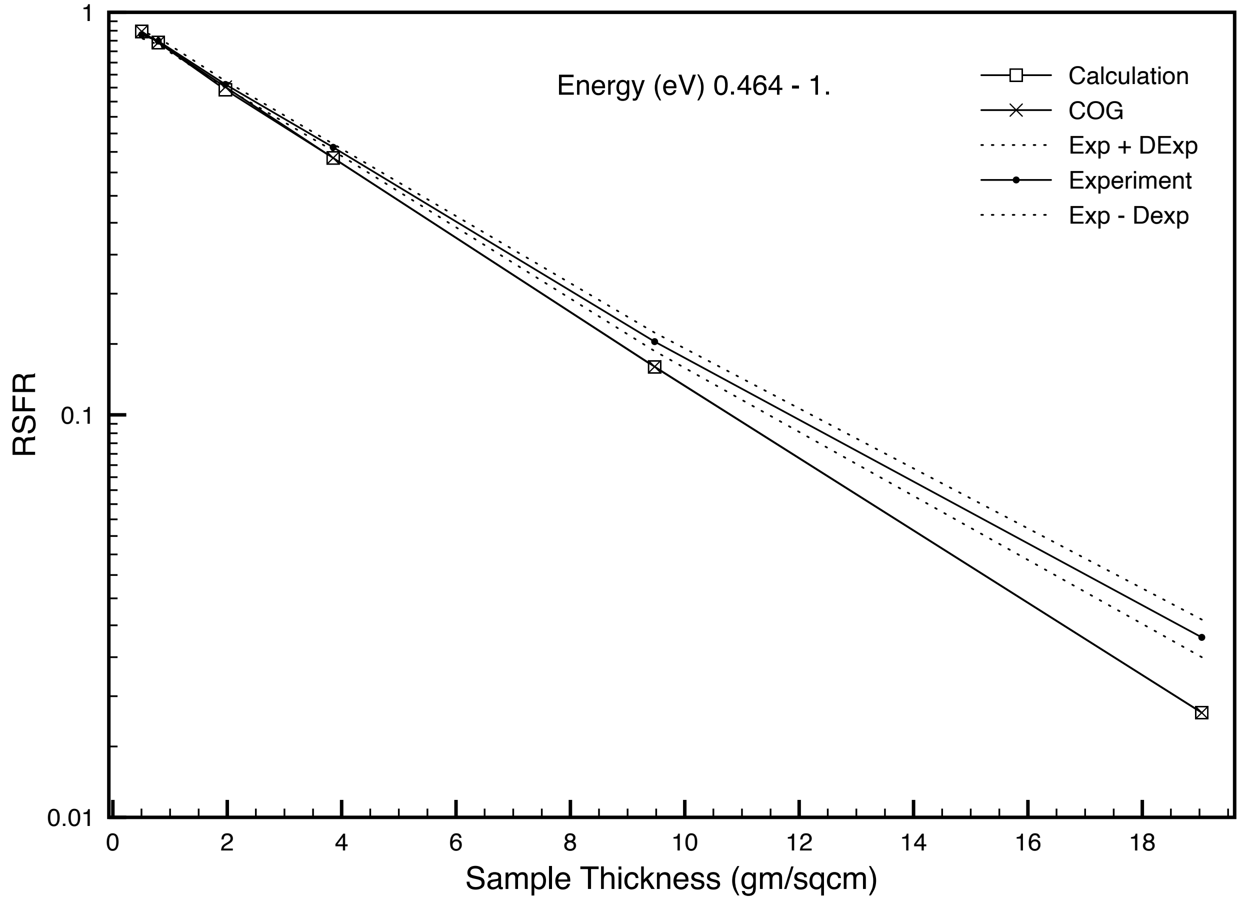
Since $\phi = 1/E$, the relative shielding fission rate in each group can be expressed analytically as:

$$R(x,G) = \frac{\int_{E_G}^{2.15E_G} \sigma_F(E)\exp[-\Sigma_T(E)\,x]\,\frac{dE}{E}}{\int_{E_G}^{2.15E_G} \sigma_F(E)\,\frac{dE}{E}}$$

Ed Lent has integrated the ENDF/B-VIII.0 cross-sections numerically and compared these analytic results to COG Monte-Carlo calculations, which are in excellent agreement with the ratio |COG/Cal| < 2% in all cases. These results are also compared to benchmark (experimental) values in the following plots, which shows the energies where the cross-section needs improvement (e.g., 0.464 ≤ E ≤ 2.15 eV) and where it appears to be excellent (e.g., E ≥ 21.5 eV).

Energy (eV)	Sample Thickness	Exp + DExp	Experiment	Exp- Dexp	Numerical Calcultion	COG	COG/Cal
0.464 - 1.	19.04	0.031	0.028	0.025	0.0182	0.0182	1.0000
	9.473	0.160	0.152	0.144	0.1315	0.1317	1.0023
	3.852	0.471	0.462	0.453	0.4346	0.4346	1.0000
	1.968	0.675	0.662	0.649	0.6419	0.6523	1.0162
	0.794	0.865	0.848	0.831	0.8412	0.8412	1.0000
	0.504	0.898	0.880	0.862	0.8960	0.8961	1.0001
1. - 2.15	19.04	0.079	0.072	0.065	0.0607	0.0608	1.0016
	9.473	0.209	0.199	0.189	0.1787	0.1791	1.0022
	3.852	0.462	0.453	0.444	0.4424	0.4429	1.0011
	1.968	0.686	0.672	0.658	0.6452	0.6461	1.0014
	0.794	0.857	0.840	0.823	0.8334	0.8338	1.0005
	0.504	0.916	0.898	0.880	0.8900	0.8904	1.0004
2.15 - 4.64	19.04	0.152	0.131	0.124	0.1373	0.1373	1.0000
	9.473	0.305	0.286	0.267	0.3138	0.3138	1.0000
	3.852	0.562	0.527	0.492	0.5796	0.5800	1.0007
	1.968	0.748	0.719	0.690	0.7435	0.7442	1.0009
	0.794	0.909	0.874	0.839	0.8827	0.8832	1.0006
	0.504	0.943	0.924	0.905	0.9231	0.9228	0.9997
4.64 - 10.	19.04	0.029	0.025	0.021	0.0296	0.0297	1.0034
	9.473	0.075	0.070	0.065	0.0826	0.0828	1.0024
	3.852	0.191	0.179	0.167	0.2026	0.2030	1.0020
	1.968	0.311	0.297	0.278	0.3261	0.3270	1.0028
	0.794	0.548	0.514	0.480	0.5359	0.5364	1.0009
	0.504	0.644	0.631	0.618	0.6460	0.6462	1.0003

10. - 21.5	19.04	0.036	0.034	0.032	0.0398	0.0399	1.0025
	9.473	0.109	0.103	0.097	0.1138	0.1142	1.0035
	3.852	0.247	0.233	0.219	0.2609	0.2613	1.0015
	1.968	0.373	0.352	0.331	0.3839	0.3844	1.0013
	0.794	0.556	0.524	0.492	0.5720	0.5723	1.0005
	0.504	0.653	0.640	0.627	0.6708	0.6719	1.0016
21.5 - 46.4	19.04	0.045	0.043	0.041	0.0428	0.0429	1.0023
	9.473	0.137	0.131	0.125	0.1290	0.1293	1.0023
	3.852	0.339	0.324	0.309	0.3160	0.3163	1.0010
	1.968	0.499	0.477	0.455	0.4887	0.4889	1.0004
	0.794	0.725	0.693	0.661	0.7154	0.7105	0.9932
	0.504	0.809	0.793	0.777	0.8021	0.7962	0.9926
46.4 - 100.	19.04	0.071	0.067	0.063	0.0605	0.0606	1.0016
	9.473	0.194	0.183	0.172	0.1717	0.1719	1.0012
	3.852	0.444	0.420	0.394	0.4101	0.4105	1.0010
	1.968	0.640	0.605	0.570	0.6039	0.6037	0.9997
	0.794	0.831	0.785	0.739	0.8030	0.8025	0.9994
	0.504	0.882	0.865	0.848	0.8675	0.8677	1.0002
100. - 215.	19.04	0.104	0.099	0.094	0.0987	0.0991	1.0041
	9.473	0.274	0.260	0.246	0.2532	0.2541	1.0036
	3.852	0.553	0.524	0.495	0.5207	0.5225	1.0035
	1.968	0.759	0.719	0.679	0.6991	0.7008	1.0024
	0.794	0.915	0.867	0.819	0.8580	0.8604	1.0028
	0.504	0.916	0.898	0.880	0.9055	0.9082	1.0030
215. - 464.	19.04	0.163	0.159	0.155	0.1474	0.1482	1.0054
	9.473	0.345	0.336	0.327	0.3373	0.3395	1.0065
	3.852	0.630	0.613	0.596	0.6095	0.6132	1.0061
	1.968	0.802	0.780	0.758	0.7657	0.7706	1.0064
	0.794	0.919	0.894	0.869	0.8925	0.8974	1.0055
	0.504	0.960	0.941	0.922	0.9284	0.9329	1.0048
464. - 1000.	19.04	0.222	0.214	0.206	0.2122	0.2148	1.0123
	9.473	0.456	0.440	0.424	0.4367	0.4427	1.0137
	3.852	0.729	0.703	0.677	0.6980	0.7077	1.0139
	1.968	0.872	0.841	0.810	0.8247	0.8341	1.0114
	0.794	0.966	0.932	0.898	0.9177	0.9279	1.0111
	0.504	0.958	0.939	0.920	0.9426	0.9548	1.0129
1000. - 2150.	19.04	0.309	0.302	0.295	0.3005	0.3020	1.0050
	9.473	0.554	0.542	0.530	0.5391	0.5409	1.0033
	3.852	0.790	0.773	0.756	0.7721	0.7759	1.0049
	1.968	0.866	0.847	0.828	0.8735	0.8766	1.0035
	0.794	0.939	0.919	0.899	0.9441	0.9478	1.0039
	0.504	0.957	0.938	0.919	0.9625	0.9662	1.0038



Energy (eV) 0.464 - 1.
Calculation
COG
Exp + DExp
Experiment
Exp - Dexp
RSFR
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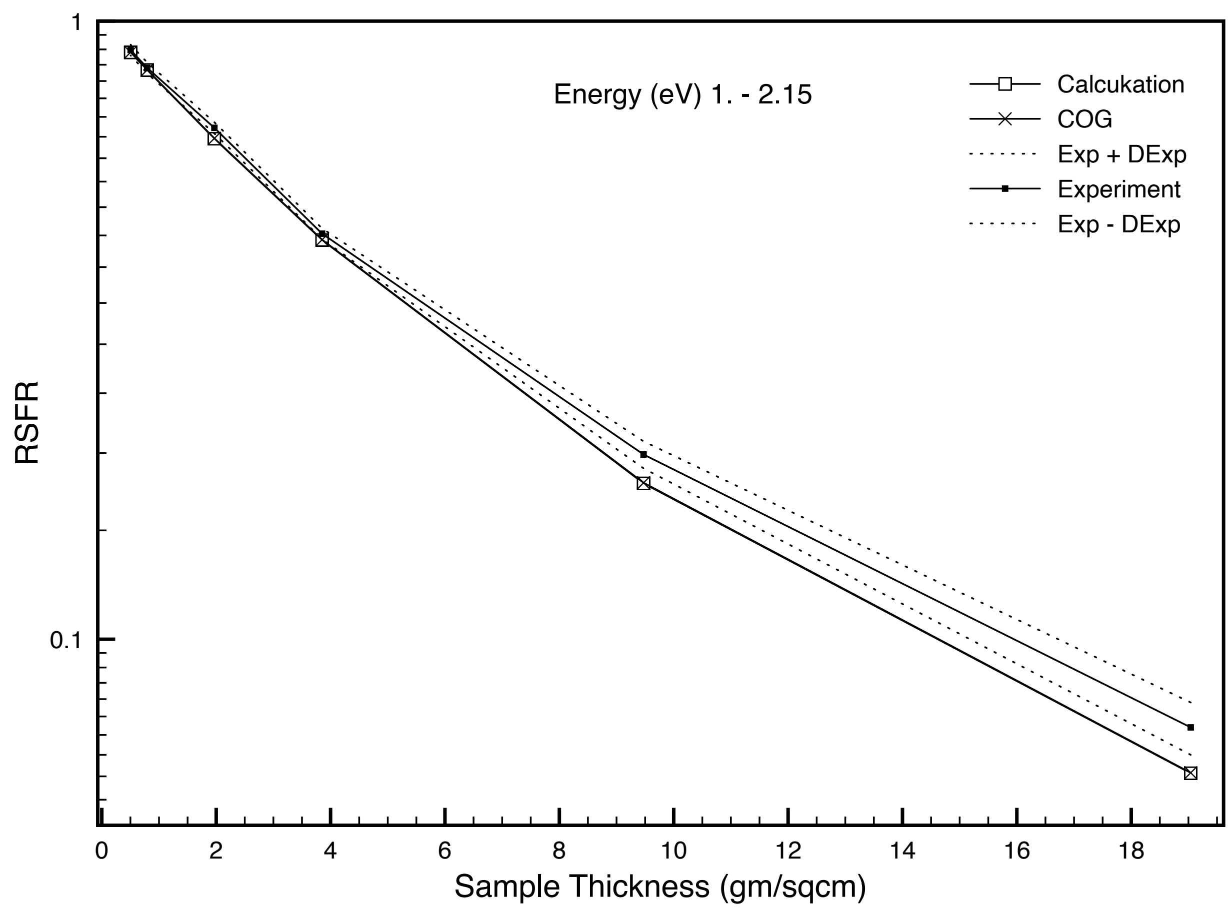
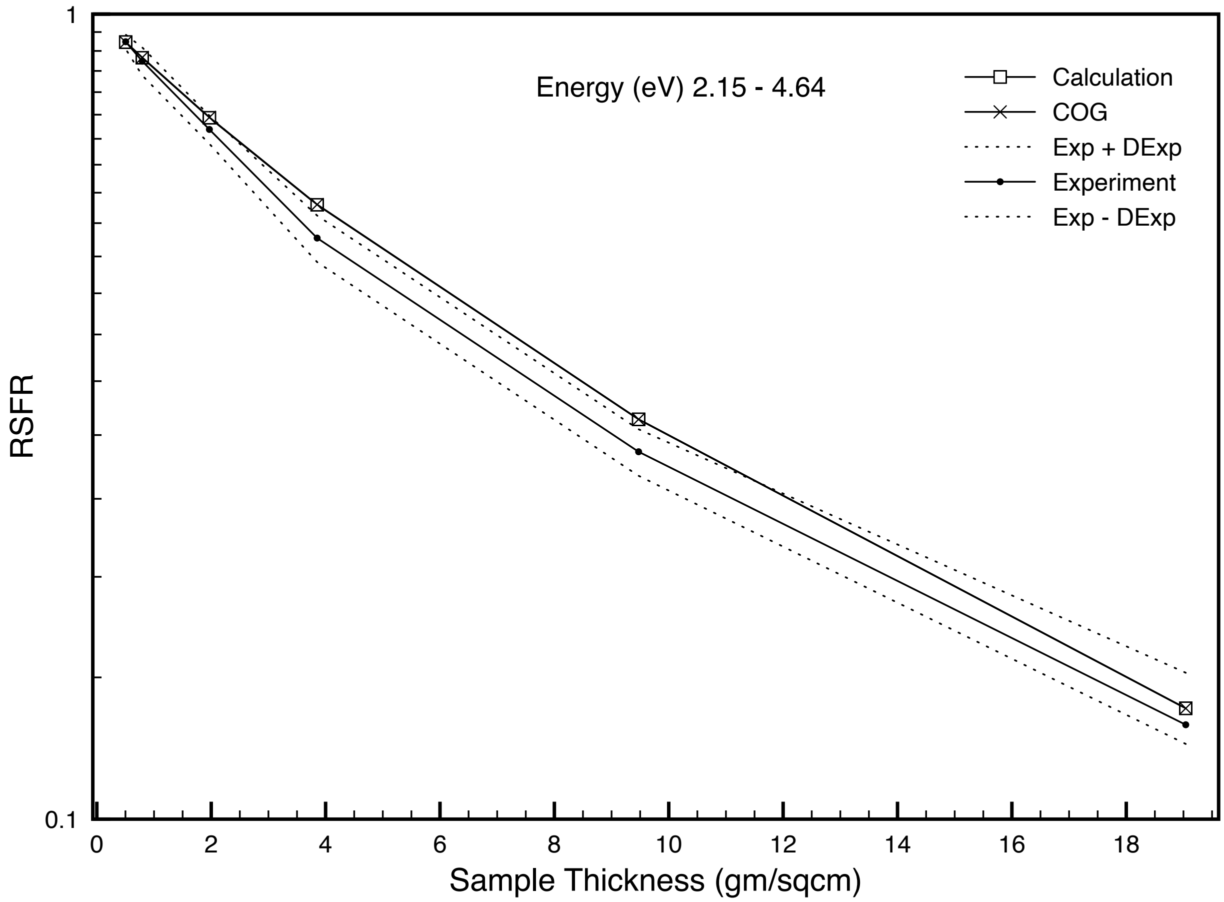
0.1
0.01
0
2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)



Energy (eV) 1. - 2.15
Calcukation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
1
0.1
0
2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)



Energy (eV) 2.15 - 4.64
Calculation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
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0
2
4
6
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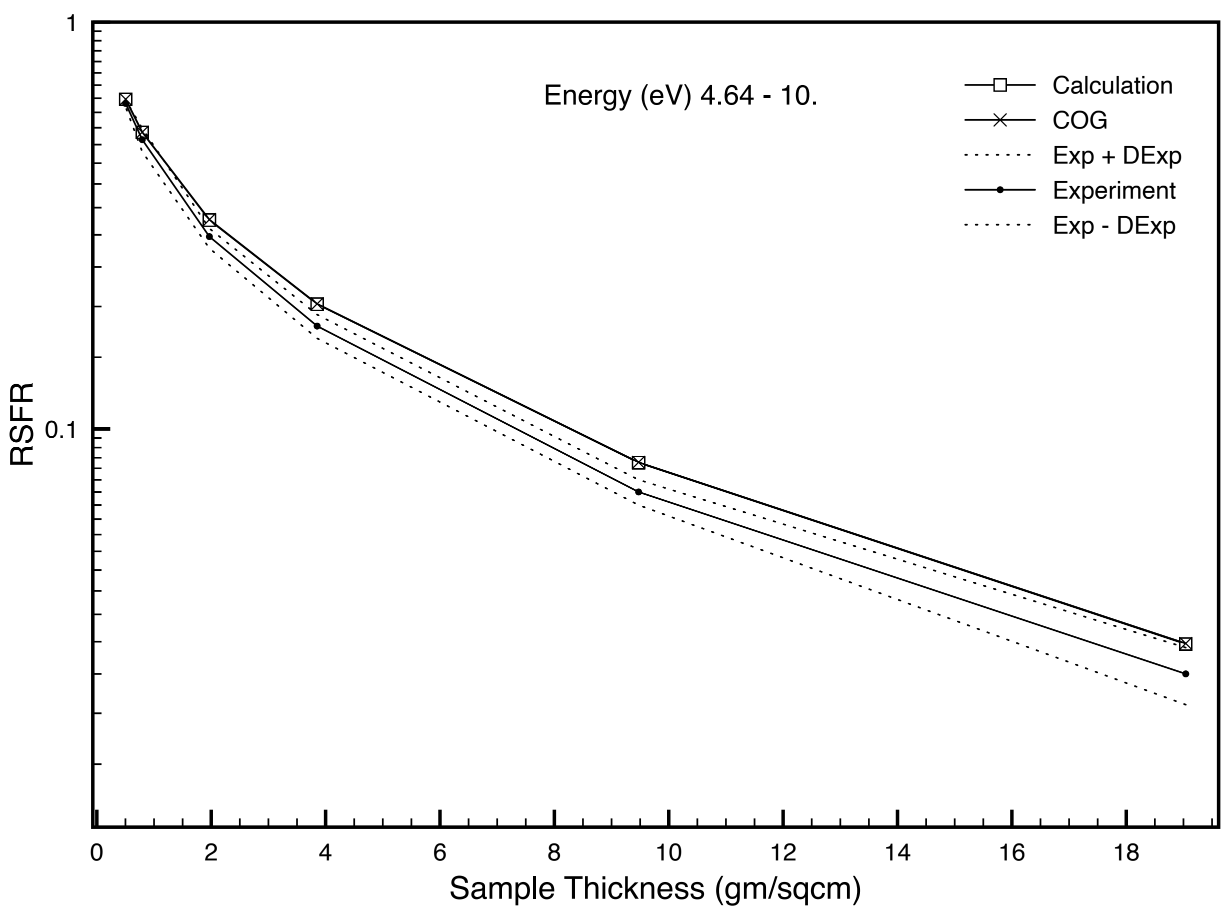
14
16
18
Sample Thickness (gm/sqcm)



Energy (eV) 4.64 - 10.
Calculation
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Exp + DExp
Experiment
Exp - DExp
RSFR
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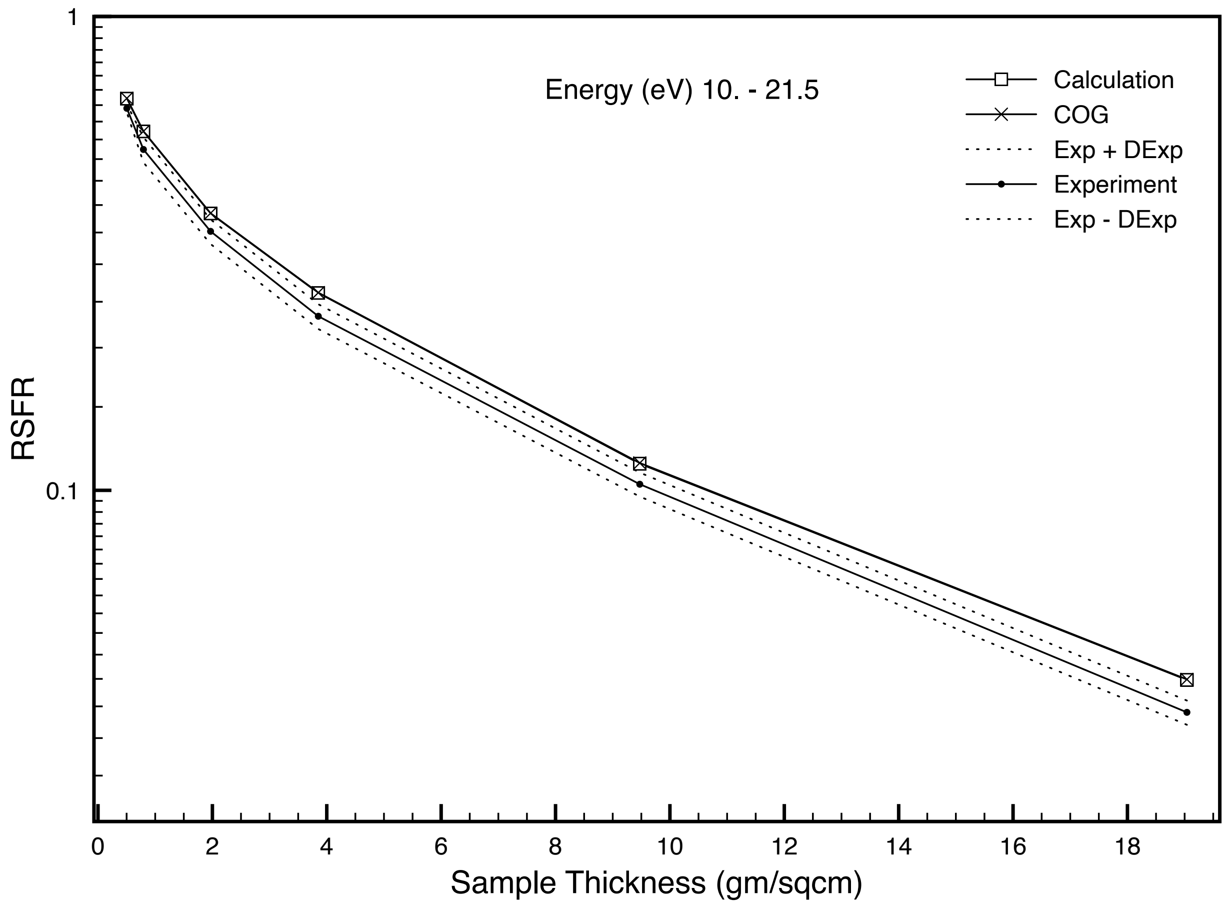
0
2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)


Energy (eV) 10. - 21.5
Calculation
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Exp + DExp
Experiment
Exp - DExp
RSFR
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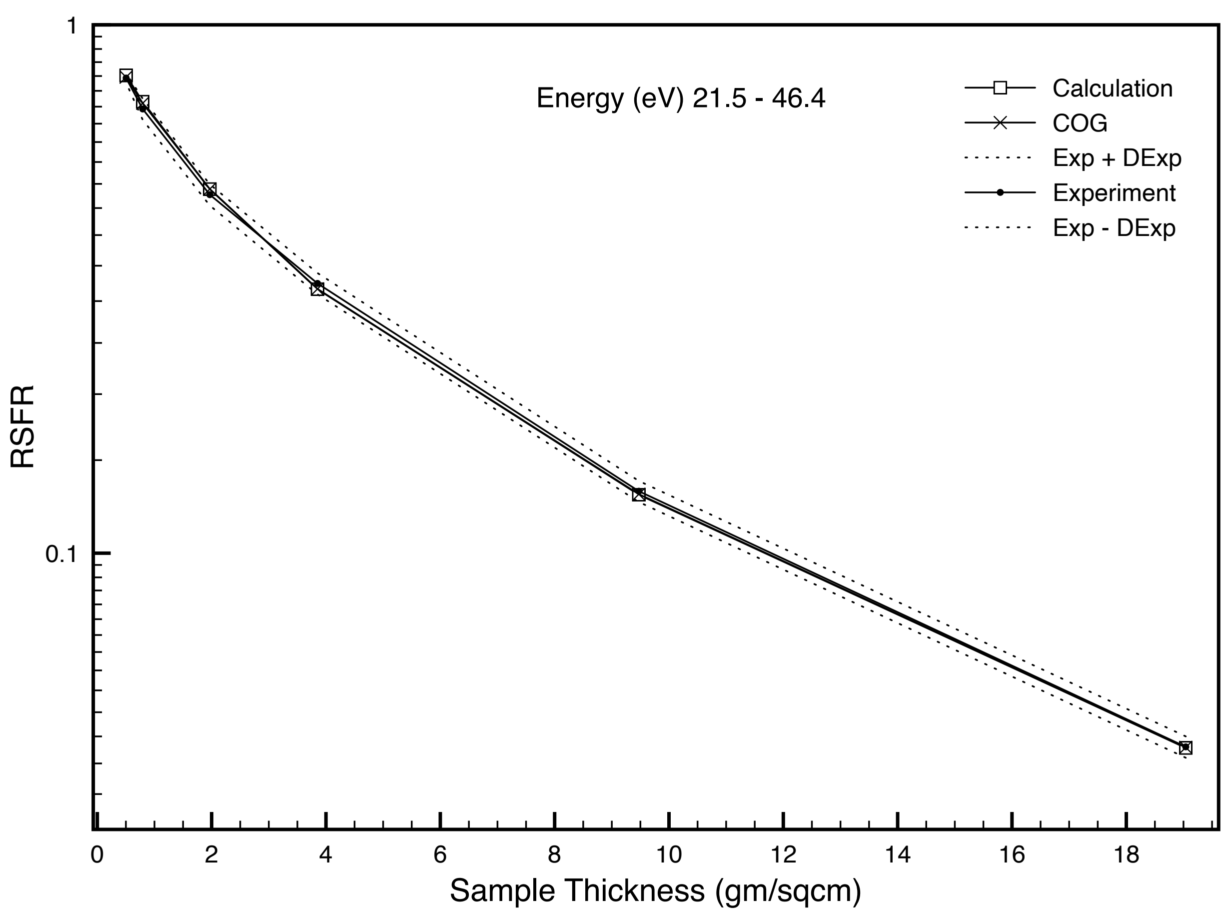
0
2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)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Calculation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
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0
2
4
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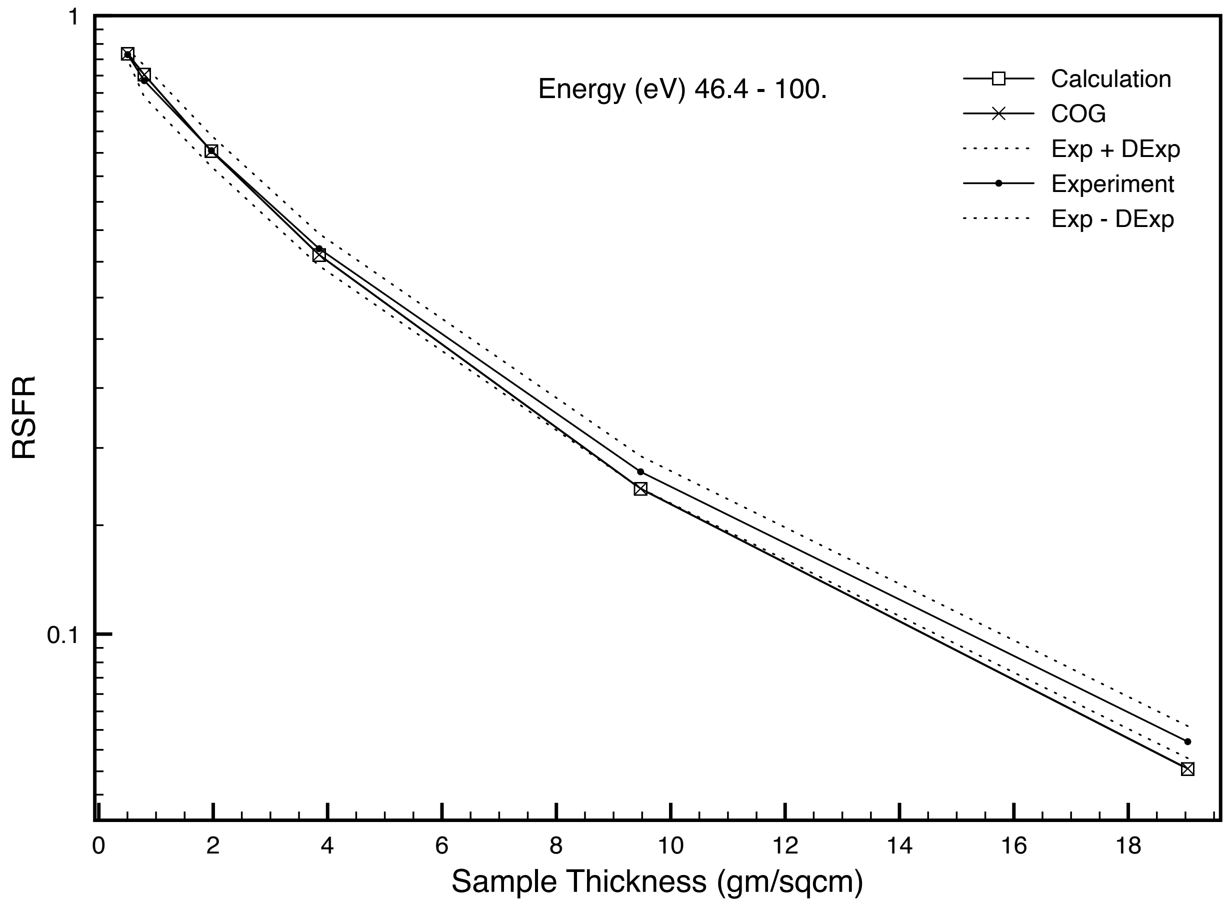
16
18
Sample Thickness (gm/sqcm)



Energy (eV) 46.4 - 100.
Calculation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
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0
2
4
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8
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12
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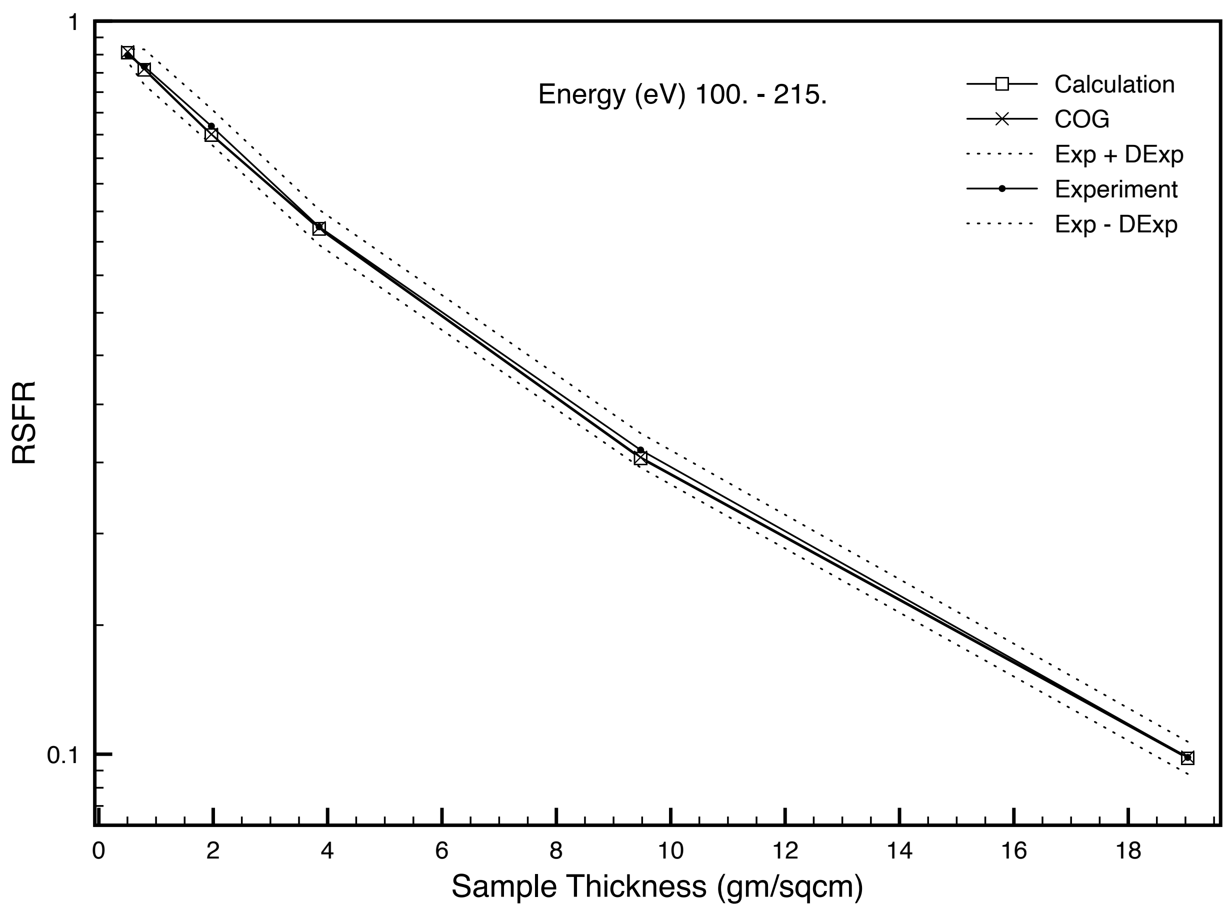
16
18
Sample Thickness (gm/sqcm)



Energy (eV) 100. - 215.
Calculation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
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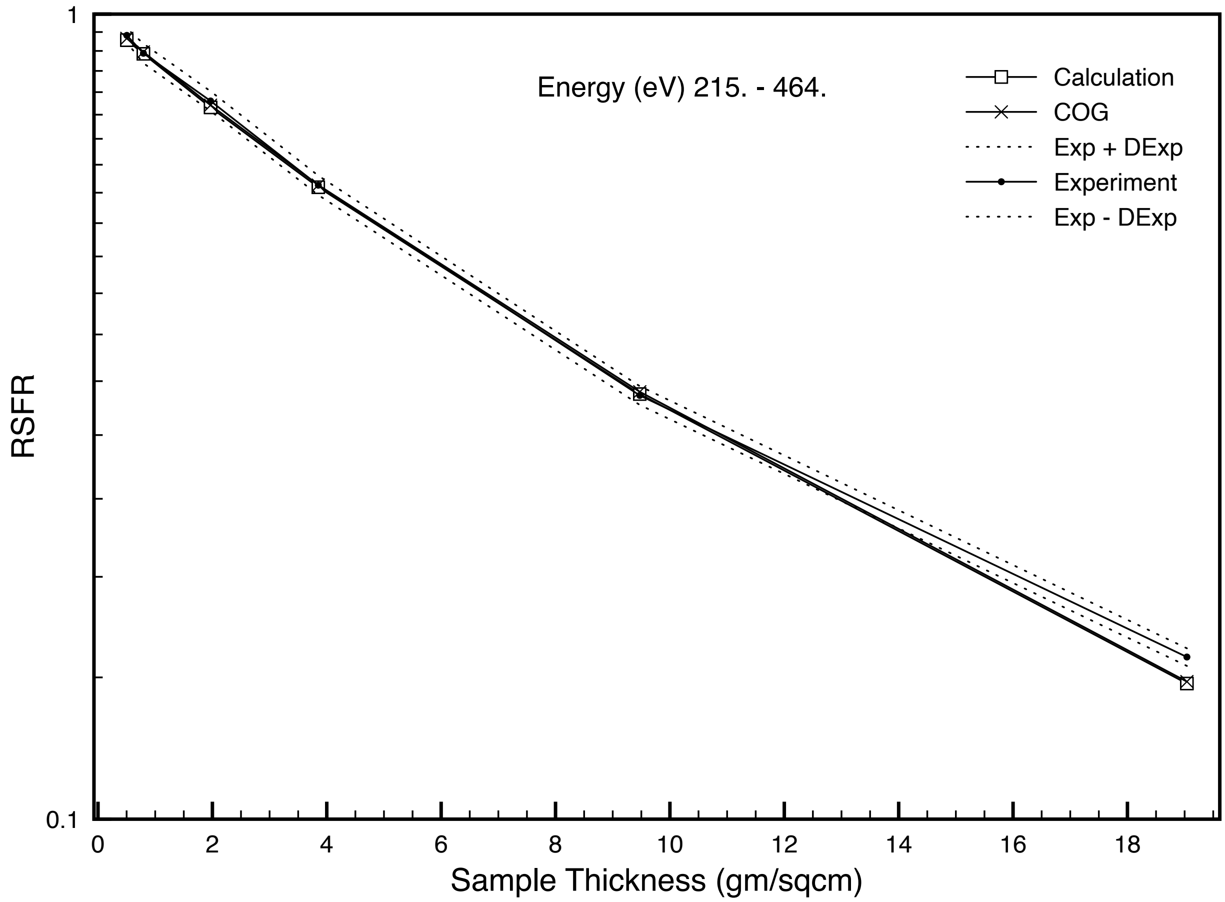
0.1
0
2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)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Calculation
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Exp + DExp
Experiment
Exp - DExp
RSFR
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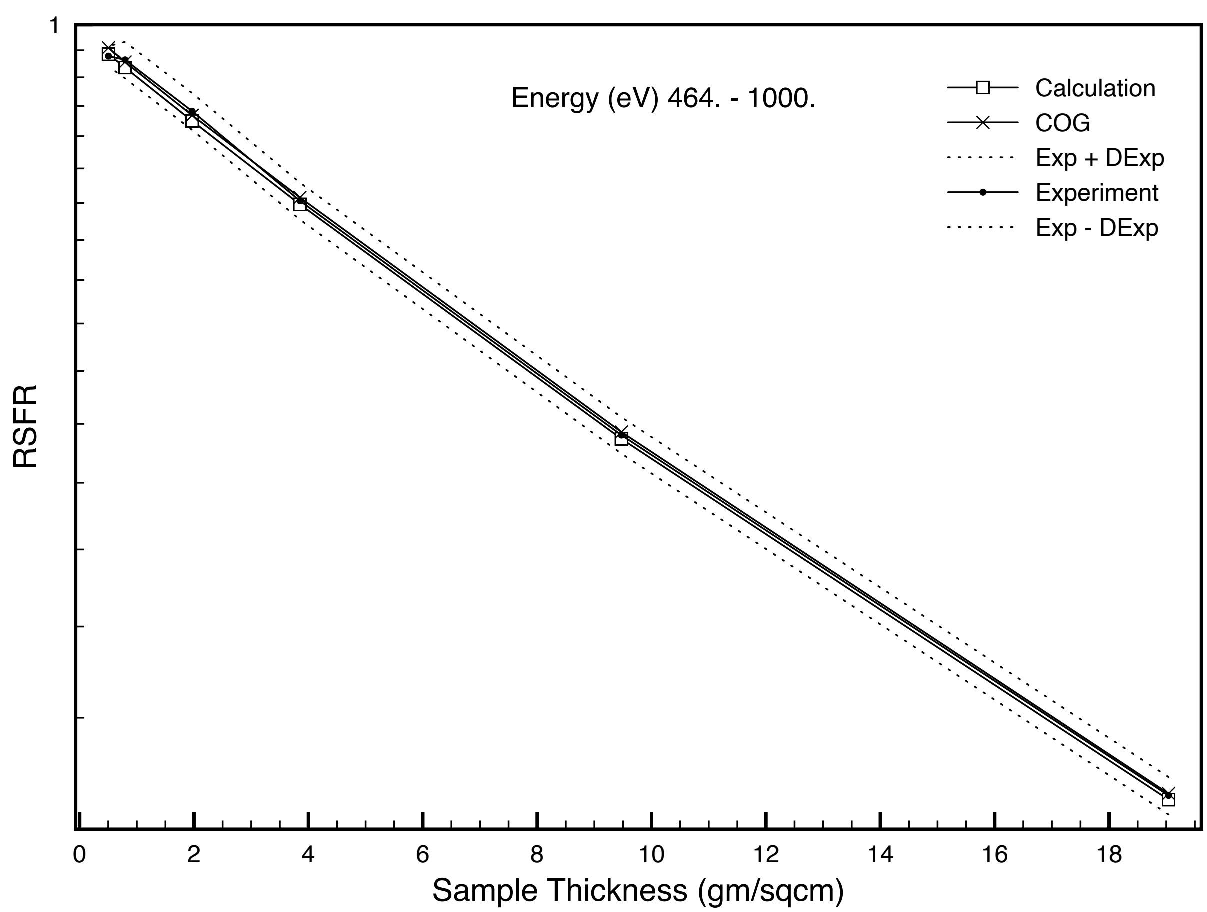
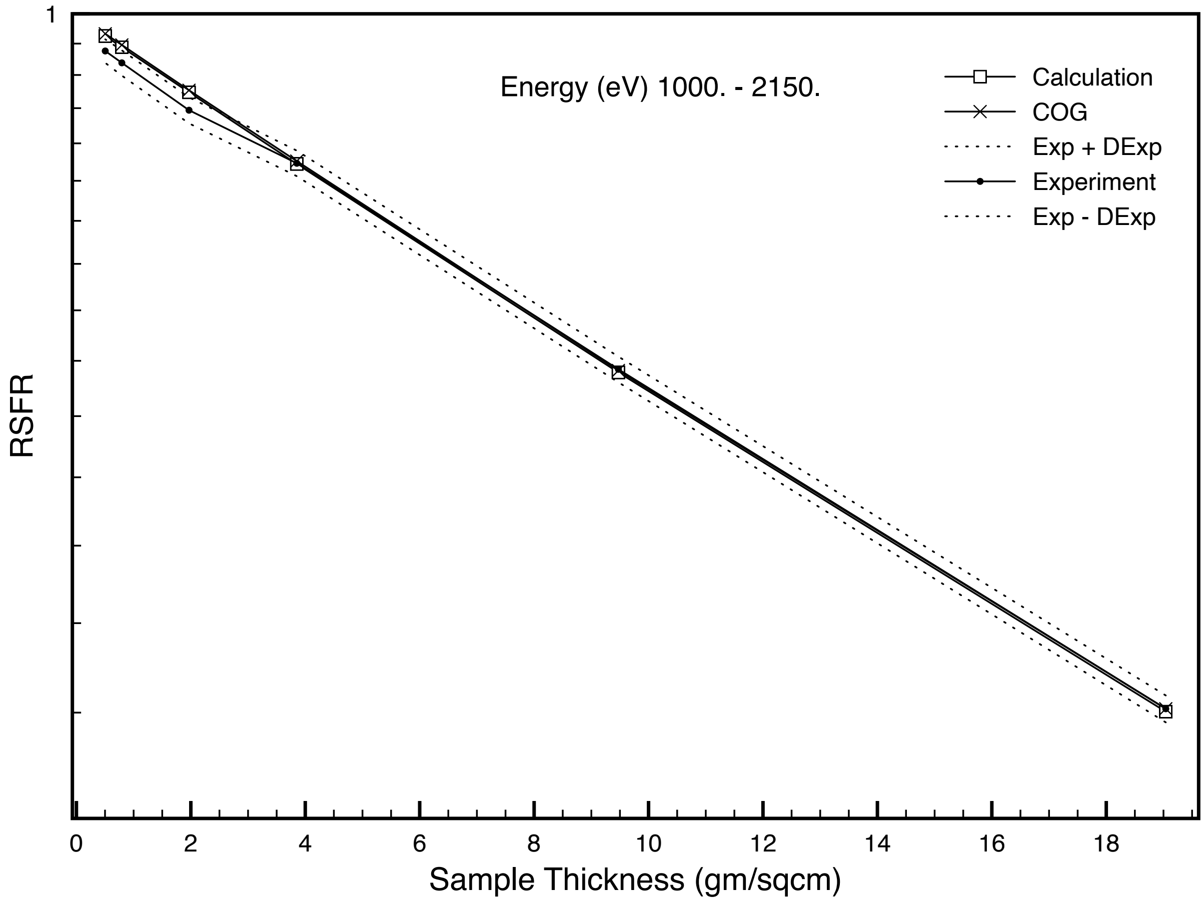
16
18
Sample Thickness (gm/sqcm)


Energy (eV) 464. - 1000.
Calculation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
1
0
2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)



Energy (eV) 1000. - 2150.
Calculation
COG
Exp + DExp
Experiment
Exp - DExp
RSFR
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2
4
6
8
10
12
14
16
18
Sample Thickness (gm/sqcm)