Summary Report for Contract TAL-NAPC20230310-001

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Introduction

This report summarizes the work performed under Contract TAL-NAPC20230310-001. Tasks undertaken include (i) perform a re-analysis of the Barber and George, reference (1) photoneutron experiment using modern (JENDL-5.0 and TENDL-2021) nuclear data libraries, and (ii) create an artificial simulation to test all JENDL-5.0 and TENDL-2021 stable isotope photonuclear data files.

Barber and George Photonuclear Experiment

Barber and George measured neutron yields from select targets of various thickness bombarded by monoenergetic electrons. Computational analysis of this experiment by Morgan, reference (2), was used in the development and implementation of photonuclear physics in the Los Alamos National Laboratory's MCNP Monte Carlo code. More recently M.Frankl and R.Macián-Juan, reference (3) used MCNP(X) and the then latest available ENDF photonuclear data libraries to re-analyze this experiment.

The Barber and George experiment has been analyzed one more time, using ENDF/B-VIII.0, JENDL-5.0 and TENDL-2021 nuclear data libraries, and MCNP6.2 (reference (4)). The computational model closely follows the Barber and George description, with similar approximations (exactly monoenergetic electron beam energy with a 1.27 cm beam diameter impinging perpendicular to the target). As done previously (see Section II.B of reference (3)), neutron yields are calculated as a neutron current (MCNP type 1 tally) through the target surface. For each target/electron beam energy combination a total of 10^8 electrons were simulated. Energy cutoffs for electrons and photons below the photonuclear threshold energies of the target were utilized to reduce CPU runtime. In addition, forced collisions for photons within the target was invoked. Target nomenclature and physical parameters are noted in Table 1 below.

Table 1: Barber and George Experiment Target Information					
Element	**Density, g/cm³**	**Target**	**Thickness**		**# of Discrete e⁻ Beam Energies and Values (MeV)**
			g/cm²	MCNP model (cm)	
Carbon	2.20	C-I	38.91	17.6864	3, at 26.0, 28.3, 34.4
Aluminum	2.70	Al-I	24.19	8.9593	3, at 22.2, 28.3, 34.3
Copper	8.92	Cu-A	1.372	0.1538	7, from 13.9 to 31.9
		Cu-I	13.26	1.4865	5, from 16.1 to 35.5
		Cu-II	26.56	2.9776	4, from 16.1 to 34.4
		Cu-III	39.86	4.4686	4, from 16.1 to 34.4
		Cu-IV	53.13	5.9563	4, from 16.1 to 34.4
Tantalum	16.6	Ta-I	6.21	0.3741	4, from 10.3 to 34.3
Lead	11.34	Pb-I	5.88	0.5185	3, at 18.7, 28.3, 34.5
		Pb-II	11.42	1.0071	3, at 18.7, 28.3, 34.5
		Pb-III	17.30	1.5256	3, at 18.7, 28.3, 34.5
		Pb-IV	22.89	2.0185	3, at 18.7, 28.3, 34.5
		Pb-VI	34.42	3.0353	3, at 18.7, 28.3, 34.5
Uranium	18.95	U-I	6.17	0.3256	4, from 16.4 to 35.5
		U-II	12.42	0.6554	4, from 16.4 to 35.5
		U-III	18.61	0.9821	5, from 11.5 to 35.5

The MCNP calculation of the Barber and George experiment is a “mode e p n” calculation. Hence data libraries for electrons (##e), photons (##p), neutrons (##c) and photonuclear (##u) cross sections are required. The specific library files used for ENDF/B-VIII.0 (E80), JENDL-5.0 (J50) and TENDL-2021 (T21) calculations are noted in Table 2.

Table 2: Library Data Files			
Library	**ZAID Suffix**	**ID**	**Data Source**
ENDF/B-VIII.0	elib = 03e plib=14p nlib=00c pnlib=70u	LANL “el03” LANL “eprdata14” LANL “Lib80x” LANL “ENDF7u”	LANL ACE files downloaded from https://nucleardata.lanl.gov/libraries/ace/.
JENDL-5 (J50)	elib=03e plib=20p nlib=20c pnlib=20u	LANL “el03” J50 J50 J50	JENDL-5 ACE files downloaded from https://wwwndc.jaea.go.jp/jendl/j5/j5.html. LANL (E80) data used for electro-atomic data.
TENDL-2021 (T21)	elib=03e plib=14p nlib=21c pnlib=21u	LANL “el03” LANL “eprdata14” T21 T21	TENDL-2021 ACE files downloaded from https://tendl.web.psi.ch/tendl_2021/tendl2021.html. LANL (E80) data used for electrons and photons.

Results from the various MCNP calculations are provided in the Table below. As an additional point of comparison previous results by M.Frankl and R.Macián-Juan are included in the "ENDF7U" column. The "E80" results closely mimic "ENDF7U". This is expected as there has been little change in the atomic and nuclear data since M.Frankl and R.Macián-Juan's work.

Results for E80 and J50 are similar, with J50 doing better for the Uranium targets. In contrast the T21 Carbon and Uranium results are significantly worse than E80 and J50 while T21 Aluminum is significantly better.

Benchmarking and data testing of evaluated photonuclear data libraries has not been a priority in recent years. It is hoped that this work will lead to greater involvement by the technical community in coming years.

Experimental and Calculated Neutron Yields													
Target	Energy (MeV)	Neutron Yield per 10^6 Electrons											
		Expt.	Expt. Unc	ENDF7U	**E80**	E80 Unc	Diff, % (E80-Expt)	**JENDL-5**	JENDL-5 Unc	Diff, % (J5-Expt)	**TENDL-2021**	TENDL-2021 Unc	Diff, % (T21-Expt)
C - I	26.0	**31**	5	23	**22.78**	0.32	-26.5%	**22.46**	0.32	-27.5%	**8.57**	0.20	-72.4%
	28.3	**60**	9	49	**47.94**	0.47	-20.1%	**45.29**	0.45	-24.5%	**16.63**	0.27	-72.3%
	34.4	**173**	26	148	**143.19**	0.80	-17.2%	**127.74**	0.75	-26.2%	**47.03**	0.45	-72.8%
Al - I	22.2	**46**	7	35	**34.15**	0.37	-25.8%	**34.37**	0.37	-25.3%	**50.31**	0.45	9.4%
	28.3	**210**	32	158	**153.05**	0.78	-27.1%	**152.70**	0.78	-27.3%	**221.95**	0.93	5.7%
	34.3	**430**	65	329	**318.88**	1.12	-25.8%	**314.09**	1.10	-27.0%	**463.77**	1.34	7.9%
Cu - A	13.9	**1.1**	0.2	0.7	**0.66**	0.06	-39.7%	**0.77**	0.06	-30.2%	**0.73**	0.06	-33.9%
	16.3	**3.6**	0.5	2.9	**2.83**	0.12	-21.4%	**3.01**	0.12	-16.3%	**2.85**	0.12	-20.8%
	19.9	**11.8**	1.8	8.9	**8.85**	0.21	-25.0%	**9.05**	0.21	-23.3%	**8.63**	0.21	-26.9%
	23.5	**21.1**	3.2	14.5	**14.33**	0.27	-32.1%	**14.73**	0.27	-30.2%	**14.23**	0.27	-32.6%
	25.9	**26.3**	3.9	17.7	**17.56**	0.30	-33.2%	**18.12**	0.30	-31.1%	**17.58**	0.30	-33.2%
	28.2	**30.9**	4.6	20.2	**20.25**	0.32	-34.5%	**20.97**	0.33	-32.1%	**20.33**	0.32	-34.2%
	31.9	**35.8**	5.4	23.2	**22.90**	0.34	-36.0%	**23.79**	0.34	-33.5%	**23.36**	0.34	-34.7%
Cu - I	16.1	**30**	5	41	**40.08**	0.38	33.6%	**42.60**	0.39	42.0%	**40.59**	0.38	35.3%
	21.2	**260**	39	268	**260.82**	0.97	0.3%	**267.09**	0.96	2.7%	**253.85**	0.94	-2.4%
	28.3	**820**	123	765	**737.06**	1.62	-10.1%	**758.59**	1.67	-7.5%	**730.89**	1.68	-10.9%
	34.4	**1290**	194	1165	**1129.45**	2.03	-12.4%	**1170.12**	2.11	-9.3%	**1141.35**	2.17	-11.5%
	35.5	**1390**	209	1228	**1192.61**	2.15	-14.2%	**1237.51**	2.23	-11.0%	**1210.71**	2.18	-12.9%
Cu - II	16.1	**50**	8	68	**67.55**	0.63	35.1%	**71.64**	0.64	43.3%	**68.46**	0.63	36.9%
	21.2	**430**	65	460	**447.59**	0.05	4.1%	**458.58**	0.05	6.6%	**436.20**	1.61	1.4%
	28.3	**1390**	209	1375	**1322.97**	2.91	-4.8%	**1360.69**	2.86	-2.1%	**1311.25**	2.88	-5.7%
	34.4	**2370**	356	2194	**2118.92**	3.60	-10.6%	**2194.19**	3.73	-7.4%	**2136.95**	3.63	-9.8%

Cu - III	16.1	**70**	11	86	**84.93**	0.79	21.3%	**90.11**	0.81	28.7%	**86.11**	0.79	23.0%
	21.2	**530**	80	580	**563.66**	2.03	6.4%	**577.91**	2.08	9.0%	**549.76**	2.03	3.7%
	28.3	**1800**	270	1754	**1684.91**	3.54	-6.4%	**1732.52**	3.64	-3.7%	**1669.84**	3.67	-7.2%
	34.4	**2930**	440	2834	**2730.96**	4.64	-6.8%	**2827.07**	4.81	-3.5%	**2752.84**	4.68	-6.0%
Cu - IV	16.1	**100**	15	97	**95.80**	0.89	-4.2%	**101.60**	0.91	1.6%	**97.16**	0.89	-2.8%
	21.2	**600**	90	655	**636.38**	2.29	6.1%	**652.04**	2.35	8.7%	**620.68**	2.30	3.4%
	28.3	**2130**	320	1987	**1908.85**	4.01	-10.4%	**1962.73**	4.12	-7.9%	**1892.05**	4.16	-11.2%
	34.4	**3350**	503	3227	**3109.42**	5.29	-7.2%	**3218.18**	5.47	-3.9%	**3134.06**	5.33	-6.4%
Ta - I	10.3	**80**	12	8.1	**8.05**	0.18	-89.9%	**8.39**	0.19	-89.5%	**9.70**	0.20	-87.9%
	18.7	**520**	78	575	**556.46**	1.56	7.0%	**578.03**	1.56	11.2%	**634.41**	1.65	22.0%
	28.3	**1380**	207	1427	**1395.80**	2.65	1.1%	**1447.49**	2.61	4.9%	**1573.21**	2.83	14.0%
	34.3	**1810**	272	1718	**1689.71**	2.87	-6.6%	**1768.02**	3.01	-2.3%	**1922.36**	3.08	6.2%
Pb - I	18.7	**730**	110	625	**604.94**	1.63	-17.1%	**592.90**	1.60	-18.8%	**560.93**	1.57	-23.2%
	28.3	**1690**	254	1360	**1331.58**	2.53	-21.2%	**1302.67**	2.48	-22.9%	**1286.20**	2.44	-23.9%
	34.5	**2120**	318	1605	**1579.68**	2.69	-25.5%	**1544.42**	2.78	-27.2%	**1558.70**	2.81	-26.5%
Pb - II	18.7	**1320**	198	1131	**1090.69**	2.40	-17.4%	**1069.30**	2.35	-19.0%	**1010.86**	2.32	-23.4%
	28.3	**3450**	518	2860	**2772.57**	3.88	-19.6%	**2712.67**	3.80	-21.4%	**2666.98**	4.00	-22.7%
	34.5	**4720**	708	3705	**3599.16**	4.68	-23.7%	**3518.61**	4.57	-25.5%	**3524.24**	4.58	-25.3%
Pb - III	18.7	**1770**	266	1487	**1440.83**	3.17	-18.6%	**1412.32**	3.11	-20.2%	**1335.27**	3.07	-24.6%
	28.3	**4690**	704	3906	**3800.77**	5.32	-19.0%	**3719.29**	5.21	-20.7%	**3652.77**	5.48	-22.1%
	34.5	**6460**	969	5203	**5073.81**	6.09	-21.5%	**4961.88**	5.95	-23.2%	**4957.58**	6.44	-23.3%
Pb - IV	18.7	**2100**	317	1729	**1671.53**	3.68	-20.4%	**1638.30**	3.60	-22.0%	**1548.96**	3.56	-26.2%
	28.3	**5370**	806	4613	**4476.31**	6.27	-16.6%	**4380.12**	6.13	-18.4%	**4299.62**	6.02	-19.9%
	34.5	**7770**	1166	6220	**6046.02**	7.26	-22.2%	**5912.67**	7.10	-23.9%	**5901.01**	7.67	-24.1%
Pb - VI	18.7	**2500**	375	2021	**1956.86**	4.31	-21.7%	**1917.79**	4.22	-23.3%	**1813.15**	4.17	-27.5%
	28.3	**6670**	1000	5465	**5308.56**	7.43	-20.4%	**5195.10**	7.27	-22.1%	**5095.69**	7.13	-23.6%
	34.5	**9000**	1350	7453	**7252.95**	8.70	-19.4%	**7093.56**	8.51	-21.2%	**7069.13**	8.48	-21.5%
U - I	16.4	**1070**	161	1043	**1006.66**	2.62	-5.9%	**1128.07**	2.82	5.4%	**476.92**	1.57	-55.4%
	21.1	**2330**	350	2143	**2076.01**	3.94	-10.9%	**2265.79**	4.08	-2.8%	**1007.79**	2.42	-56.7%

	28.4	**3860**	579	3272	**3250.04**	4.88	-15.8%	**3515.78**	4.92	-8.9%	**1578.11**	3.00	-59.1%
	35.5	**4880**	732	3904	**3973.63**	5.56	-18.6%	**4262.35**	5.54	-12.7%	**1938.66**	3.30	-60.3%
U - II	16.4	**1950**	293	1844	**1779.65**	4.45	-8.7%	**1991.08**	4.58	2.1%	**839.73**	2.52	-56.9%
	21.1	**4310**	647	4005	**3873.17**	6.97	-10.1%	**4225.52**	7.18	-2.0%	**1872.19**	3.93	-56.6%
	28.4	**7850**	1178	6838	**6726.83**	9.42	-14.3%	**7296.31**	9.49	-7.1%	**3257.39**	5.21	-58.5%
	35.5	**10735**	1610	9029	**9063.43**	10.88	-15.6%	**9756.04**	10.73	-9.1%	**4399.09**	6.16	-59.0%
U - III	11.5	**380**	57	347	**339.45**	2.00	-10.7%	**415.98**	2.16	9.5%	**153.86**	1.03	-59.5%
	16.4	**2530**	380	2366	**2284.25**	5.71	-9.7%	**2555.40**	5.88	1.0%	**1075.28**	3.23	-57.5%
	21.1	**5900**	885	5203	**5033.61**	8.56	-14.7%	**5490.23**	8.78	-6.9%	**2424.59**	5.09	-58.9%
	28.4	**10460**	1569	9130	**8974.00**	11.67	-14.2%	**9730.26**	12.65	-7.0%	**4333.52**	6.93	-58.6%
	35.5	**14940**	2241	12396	**12404.4**	13.64	-17.0%	**13362.5**	14.70	-10.6%	**6003.54**	8.40	-59.8%

References

1. W.C.Barber and W.D.George, "Neutron Yields from Targets Bombarded by Electrons," Physical Review, **116**(6), 1551-1559, December 1959.
2. M.C.White, "Development and Implementation of Photonuclear Cross-Section Data for Mutually Coupled Neutron-Photon Transport Calculations in the Monte Carlo N-Particle (MCNP) Radiation Transport Code," LA-13744-T, July 2000.
3. M.Frankl and R.Macián-Juan, "Photonuclear Benchmarks of C, Al, Cu, Ta, Pb and U from the ENDF/B-VII Cross Section Library ENDF7U Using MCNPX," Nuclear Science and Engineering, **183**(1), 135-142, May 2016, DOI: 10.13182/NSE15-47.
4. C.J.Werner, editor, "MCNP User's Manual, Code Version 6.2," LA-UR-17-29981, October 2017.
5. Atomic and Nuclear Data Properties by the Lawrence Berkeley Laboratory Particle Data Group, available at https://pdg.lbl.gov/2009/AtomicNuclearProperties/.