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Neutron and Gamma Radiation Monitoring at The Ion Beam Laboratory, Building 720, Sandia/NM

Dann C. Ward and Mathew J. Kaspar

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Dann C. Ward and Mathew J. Kaspar
Radiation Protection Department
Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico 87185-MS1103

ABSTRACT

Neutron and gamma radiation spectra and dose rates were measured in and around the Ion Beam Laboratory, Building 720, at Sandia/NM. Measurements were made to support the testing of an enhanced target yielding 14 MeV neutrons from the deuterium-tritium (D-T) fusion reaction. The target room has thick concrete walls but an unshielded ceiling. Neutron and gamma radiation in and around the facility appear to be the result of skyshine. Estimates of neutron/gamma dose rates (per 10^9 source neutrons/s) at six (6) monitoring locations were made. Results indicated the need for enhanced radiological controls due to increased neutron production rates.

ACKNOWLEDGEMENTS

The authors thank Barney Doyle, Bruce McWatters and William Wampler for their invaluable support and guidance during the measurement process.

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EXECUTIVE SUMMARY

The development and testing of higher yield targets for the production of 14 MeV neutrons has resulted in increased neutron radiation levels in and around the Ion Beam Laboratory, Building 720, at Sandia/NM. A minor increase in associated gamma radiation levels in some locations was also detected. The target room has thick concrete walls but no shielding in the ceiling. This has resulted in neutrons exiting the room through the ceiling and being scattered back down into, and around the outside, of the facility. This effect is known as skyshine. Newer target designs are expected to have increased neutron production rates. The magnitude of the skyshine suggests that enhanced radiological controls and better shielding should be considered to accommodate the testing and development of enhanced targets.

ACRONYMS

Acronyms	Definition
MeV	Million electron volts
TLD	Thermoluminescent dosimeter

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1 INTRODUCTION

Opened in 2010, Sandia's Ion Beam Lab is a state-of-the-art facility using ion and electron accelerators to study and modify material systems.

2 PURPOSE

A new series of Deuterium-Tritium targets designed for enhanced neutron production were being evaluated. Due to the expected increase in the production of 14 MeV neutrons, there was a need to monitor representative areas in and around the Ion Beam Laboratory to characterize the resulting neutron and photon fluences and dose rates.

3 METHODOLOGY

A total of six (6) measurement locations were selected, as shown in Figure 1 below. Measurement locations were selected to reflect occupational and public radiation exposure concerns based upon discussions with health physics support personnel and building occupants. Dose and dose-rate measurements of neutron and photon radiation levels were made while the new type of target was being tested.

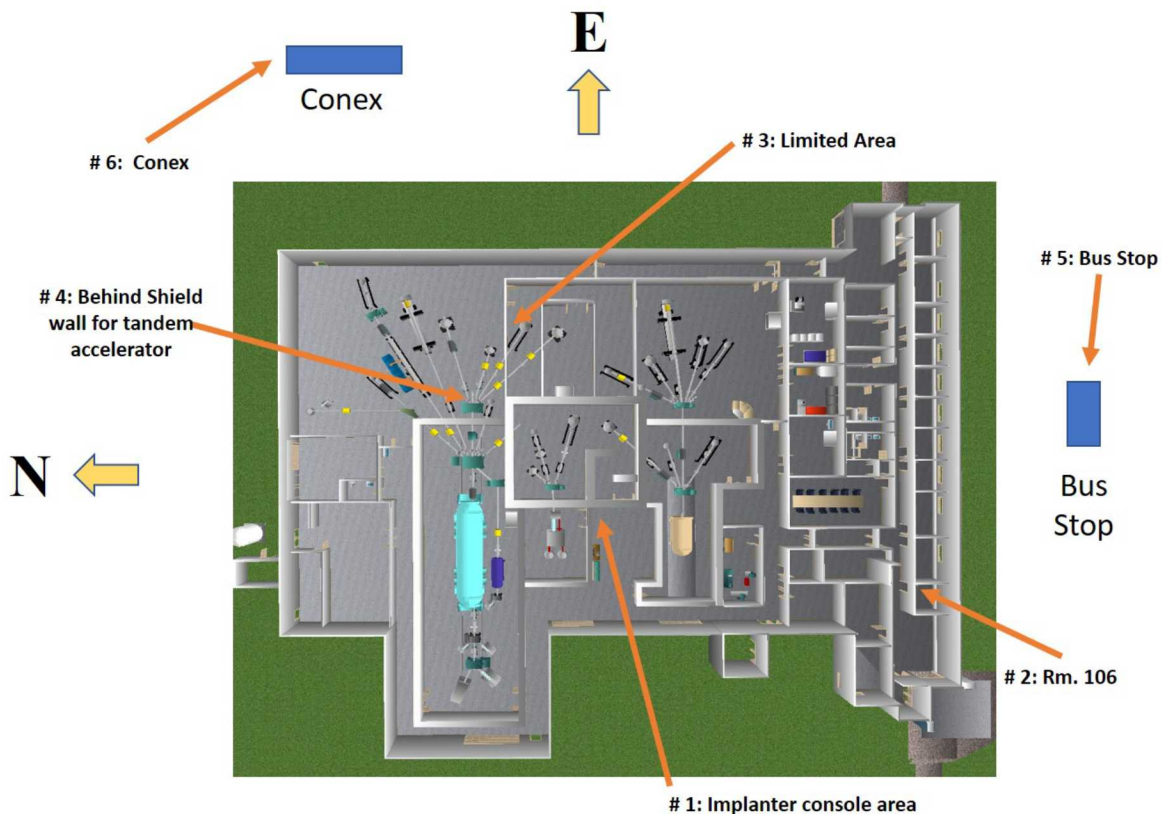


Figure 1: Layout of building 720 and the six (6) measurement locations

A Mobile Microspec Spectroscopic Gamma/Neutron Detection System was used for all measurements listed in this report. The system consisted of one G-Probe (NaI detector), one N-

Probe, an analyzer unit and a laptop computer. The equipment was placed on top of a cart so it could be wheeled between measurement locations. Additional information about the probes is

listed in Table 1. The target was operated in a continuous mode for about 4 days. Data collection times were variable between locations (See Table 2). A picture of the equipment set-up at the Implanter Control Console is shown in Figure 2.

The Mobile Microspec unit recorded raw gamma and neutron detector data. When data collection was halted, internal software unfolded the raw neutron signals and produced a fluence spectrum and a dose spectrum. A gamma spectrum was also displayed. (See Appendices A through F for monitoring data.)

Table 1: Mobile Microspec Probes

Probe	Application	Energy Range (keV)	Max Dose Rate (mrem/h)	Crystal Dimension(inches) (Thickness x Dia)
G (γ -ray)	γ and X-ray detection	50 – 3000	20	NaI, 1.5 x 1.5"
N-Probe	Neutrons	Thermal - 20000	50	2" x 2" NE213 liquid scintillator (covers the energy range 800 to 20000 keV) and sealed ^3He chamber (covers the energy range from thermal to 800 keV)

4 RESULTS

This work focused on environmental measurements of neutron and gamma radiation associated with the operation of a D-T source at the Ion Beam laboratory (Building 720). Table 2 summarizes all measurement results. It is evident that measurable levels of neutron radiation were present at all locations while elevated levels of gamma radiation were present at 3 locations close to the source. Levels decrease with distance from the source, as expected. A review of the fluence spectrums (see Appendices A through F) shows that at all measurement locations the average energy is well below the 14 MeV energy of the source neutrons. The average energy of each measured spectrum was calculated and the results summarized in section 4.7, Table 3. Average energies varied between 0.37 and 0.55 MeV.

The room which contains the neutron source has very thick concrete walls, but only a thin ceiling designed to protect against weather. As a result, 14 MeV neutrons that could travel directly to the measurement locations are highly attenuated by the thick concrete walls, while the thin ceiling allows for the creation of skyshine¹. It is expected that skyshine produces most of the neutron fluence and dose at each measurement location based upon building construction. The low average energy of the neutron spectra is consistent with a high scattering environment, i.e. skyshine.

¹ Radiation scattered by the atmosphere above a vault to points on the ground around the outside perimeter. Skyshine becomes important when a vault roof is essentially unshielded.

A discussion is presented for each measurement location. Graphs of the measured neutron fluence and spectral dose, plus the accompanying photon spectra are displayed in Appendices A through F. Calculated dose rates are presented per 10^9 source neutrons in order to allow more accurate comparisons between measurement locations and to facilitate future dose rate and total dose estimates for future planning purposes

4.1 Implanter Instrument Console Area

Initial measurements began in this area and were made during the peak of neutron output. (See Appendix H). The average neutron dose rate was 2.448 mrem/h, or 0.223 mrem/h per 10^9 source neutrons. (See Table 2). The gross measured photon dose rate was elevated above normal background and was 0.0542 mrem/h, or a net photon dose rate of 0.004 mrem/h per 10^9 source neutrons.

The combined neutron and gamma dose rate was 0.227 mrem/h per 10^9 source neutrons/s, or approximately 2 mrem per 8 h day per 10^9 source neutrons/s. Assuming future target yields in the 10^{10} neutrons/s range or greater, this would result in worker doses of approximately 20 mrem per 8 h day, or greater, around the console area.

The reason for the elevated photon dose rate was not evaluated, but it might be explained by neutron capture reactions in the concrete shield walls.

4.2 Room 106, Visitor Badge Storage Area

As shown in Table 2, measurements indicated no elevated gamma levels above normal background at a neutron production rate of 9×10^9 n/s. However, a neutron dose rate of 0.018 mrem/h per 10^9 source neutrons/s was present. The badge storage area is not shielded. (See Figure 6).

It is obvious that the badges in the storage area were being irradiated during this measurement process.

Assuming a future neutron production rate of 10^{10} neutrons/s, with stable output, and an irradiation period of 5 working days (120 hours continuous run), an estimated neutron dose at the badge storage area would be approximately 22 mrem.

4.3 Computer Work Station in Limited Area

The combined neutron and gamma dose rate was 0.195 mrem/h per 10^9 source neutrons/s. This would result in approximately 1.6 mrem per 8 h day per 10^9 source neutrons/s.

4.4 Computer Work Station Behind Shield Wall for Tandem Accelerator.

This area had the highest combined dose rate of 0.283 mrem/h per 10^9 source neutrons/s, or about 2.26 mrem per 8 hour day.

4.5 Outdoors at Bus Stop in Front of Bldg. 720

This location had a neutron dose rate of 0.014 mrem/h per 10^9 source neutrons/s. This location is not occupied in a continuous fashion, but may have individuals walking by or waiting for a bus for several minutes.

4.6 Outdoors by Conex Storage Area to The East of Bldg. 720

This location had a neutron dose rate of 0.014 mrem/h per 10^9 source neutrons/s. This location is used for long-term storage of materials and equipment and is not routinely occupied.

Table 2: Measured Neutron and Gamma Dose Rates

Spectrum # and Date Measured	Location of Measurement	Average Neutron Production Rate at target [‡] ($\times 10^9$ n/s)	Measured Neutron Dose Rate (mrem/h)	Gross Measured Photon Dose Rate (mrem/h)	Neutron Dose Rate per 10^9 n/s from target (mrem/h)/(10^9 n/s)	Net Photon Dose Rate [†] per 10^9 n/s from target (mrem/h/ 10^9 n/s)
1 (5/30/2018)	Implanter Instrument Console Area	11	2.448	0.0542	0.223	0.004
2 (5/31/2018)	Room 106, Visitor TLD Storage Area	9.0	0.166	0.0074	0.018	NDL ^{††}
3 (5/31/2018)	Computer Work Station in Limited Area	7.2	1.385	0.0307	0.192	0.003
4 (5/31/2018)	Behind Shield Wall for Tandem Accelerator	7.0	1.944	0.0436	0.278	0.005
5 (5/31/2018)	Bus Stop in Front of Building 720	6.9	0.097	0.0097	0.014	NDL
6 (6/4/2018)	Connex Storage Area to East of Bldg. 720	1.3	0.018	0.0052	0.014	NDL

[‡]See Figure 27 concerning the neutron production rate as a function of time.

[†]Normal gamma background varies between 0.006 and 0.010 mrem/h. A value of 0.010 mrem was subtracted from the gross dose rate.

^{††}No Detectable Level above background

4.7 Analysis of Measured Neutron Spectrums for Personnel Dosimetry Purposes

Table 3 indicates the average energy of the neutron field at each measurement location. The average neutron energy provides guidance in choosing a dosimeter neutron code value. See Appendix G for a more detailed discussion of how the average energy was determined.

Table 3: Average Energies of Measured Neutron Spectra at IBL

Spectrum #	Location of Measurement	E _{avg} (MeV) [†]
1	Implanter Instrument Console Area	0.37
2	Room 106, Visitor TLD Storage Area	0.55
3	Computer Work Station in Limited Area	0.39
4	Behind Shield Wall for Tandem Accelerator	0.36
5	Bus Stop in Front of Building 720	0.34
6	Connex Storage Area to East of Bldg. 720	0.42

[†]Estimated 2 σ error is $\pm 30\%$.

5 RECOMMENDATIONS

- 5.1 The measured dose rates at the implanter instrument console area, the computer work station in the limited area and behind the shield wall for the tandem accelerator are high enough to be of concern with respect to ALARA planning. Proposed output rates and longer run times for newer targets need to be considered with respect to worker and public locations and the possible need for additional radiological postings and controls.
- 5.2 Consider adding shielding around the neutron source to reduce the effects of skyshine with respect to worker dose and environmental effects beyond the IBL building.
- 5.3 The current configuration of the TLD badge storage area in room 106 is not suitable based upon the data shown in Table 2. Two options should be considered: (1) Add shielding around the badge storage area and/or the neutron source to minimize exposure to neutron radiation for the stored badges; or (2) consider moving the badge storage area to another location outside of the IBL facility.
- 5.4 The average energy values shown in Table 3 indicate that the neutron fields in and around the IBL are highly moderated. The most accurate *a priori* neutron code for IBL TLD badges is therefore “S”. The use of an “F” code will greatly over estimate whole body doses due to neutron radiation.

6 REFERENCES

Operators Manual for Mobile Microspec/Microspec6, dated 18 October 2016, Bubble Technology Industries Inc.

7 APPENDICES

- A. Monitoring Data: Implanter Control Console Area
- B. Monitoring Data: Room 106, Visitor TLD Storage Area
- C. Monitoring Data: Computer Work Station in Limited Area
- D. Monitoring Data: Behind Shield Wall for Tandem Accelerator
- E. Monitoring Data: Bus Stop In Front Of Building 720
- F. Monitoring Data: Connex Storage Area to East of Bldg. 720
- G. Average Energy of Measured Neutron Spectra
- H. Neutron Production Rate

APPENDIX A: MONITORING DATA: IMPLANTER CONTROL CONSOLE AREA

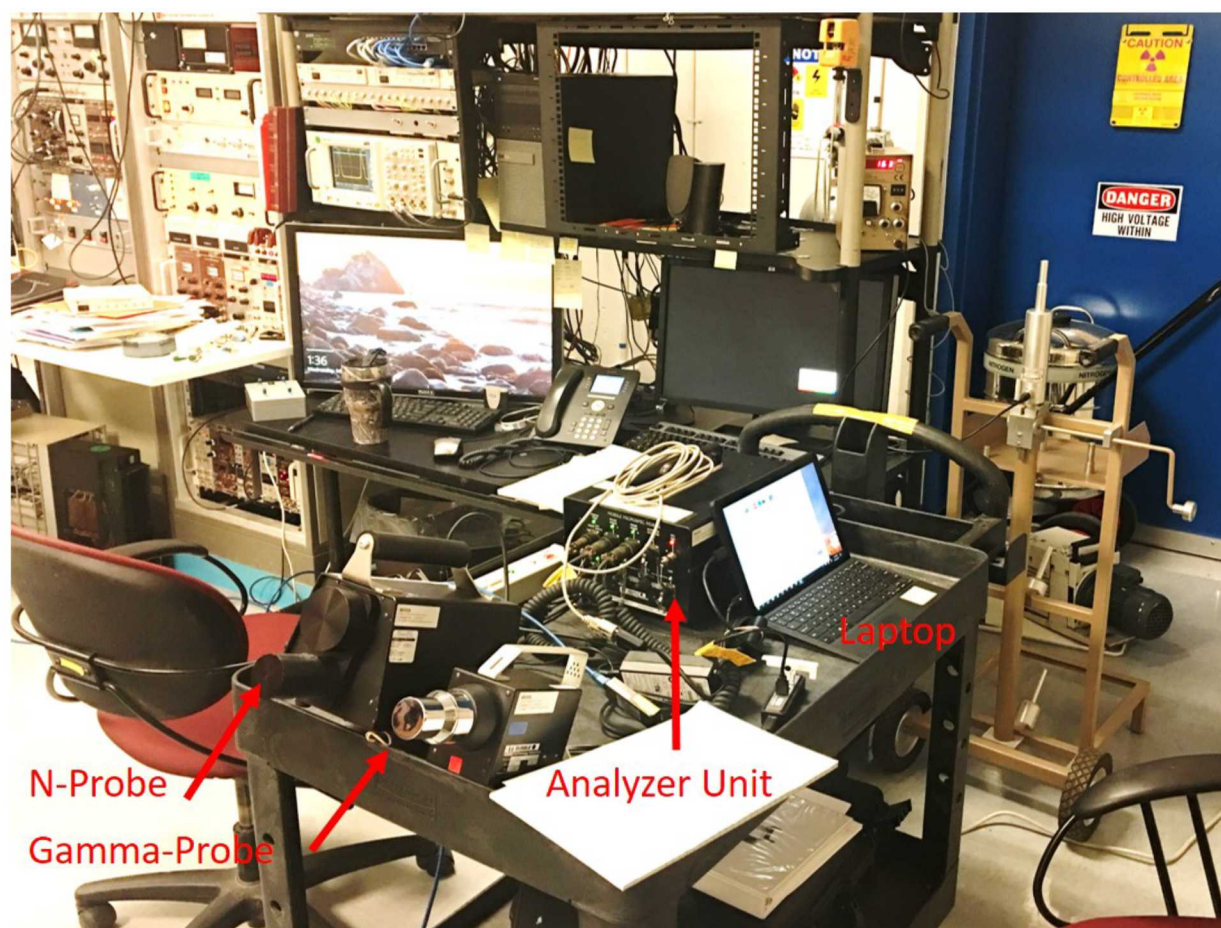


Figure 2: Equipment placement at the implanter control console.

Appendix A: Monitoring Data 30 May 2018; Implanter Control Console Area

NEUTRON DATA:

Application Version : Mobile Microspec V.6.8.2
 File Name : C:\BTIDData\May-30-2018\May-30-2018-Run-2\MAY-30-2018-RUN-2A-TOTAL.TXT
 Run Number : 2
 Time Run Started : May-30-2018 13:30:48
 Time Data Exported : May-30-2018 15:07:12
 Detector Channel : A
 Probe Type : N 2x2
 Duration (hh:mm:ss) : 01:37:16
 Calibration Gain (keV/ch) : [Hi-Gain] 4.99 ; [Lo-Gain] 51.42 ; [3He] 10.19
 Calibration Offset (ch) : [Hi-Gain] 0.00 ; [Lo-Gain] 0.00 ; [3He] 0.00
 Count Rate (/s) : [NE213] 11.4 ; [3He] 0.4
 Dead Time (%) : 4.51
 Scaler Counts : [Fast N] 60914; [Gamma] 835098; [3He] 2432
 Comments : None

UNFOLDED NEUTRON SPECTRUM

Emin (MeV)	Emax (MeV)	Fluence (1/cm ²)	Dose (mrem)	Flux (1/cm ² /s)	Dose Rate (mrem/h)
0.00	0.01	536.172	0.001	0.092	0
0.01	0.50	279800.746	3.415	47.944	2.107
0.50	1.00	660.552	0.028	0.113	0.018
1.00	1.50	460.774	0.023	0.079	0.014
1.50	2.00	1508.656	0.072	0.259	0.044
2.00	3.00	4208.944	0.196	0.721	0.121
3.00	4.00	2347.09	0.12	0.402	0.074
4.00	5.00	1146.446	0.054	0.196	0.034
5.00	6.00	553.068	0.024	0.095	0.015
6.00	7.00	384.517	0.016	0.066	0.010
7.00	8.00	281.41	0.012	0.048	0.007
8.00	9.00	137.431	0.006	0.024	0.003
9.00	10.00	27.06	0.001	0.005	0.001
10.00	12.00	19.035	0.001	0.003	0.001
12.00	14.00	-0.039	0	0	0
14.00	16.00	-0.148	0	0	0
16.00	18.00	0.431	0	0	0
18.00	20.00	-7.511	0	-0.001	0
Total:		292064.633	3.969	50.046	2.448

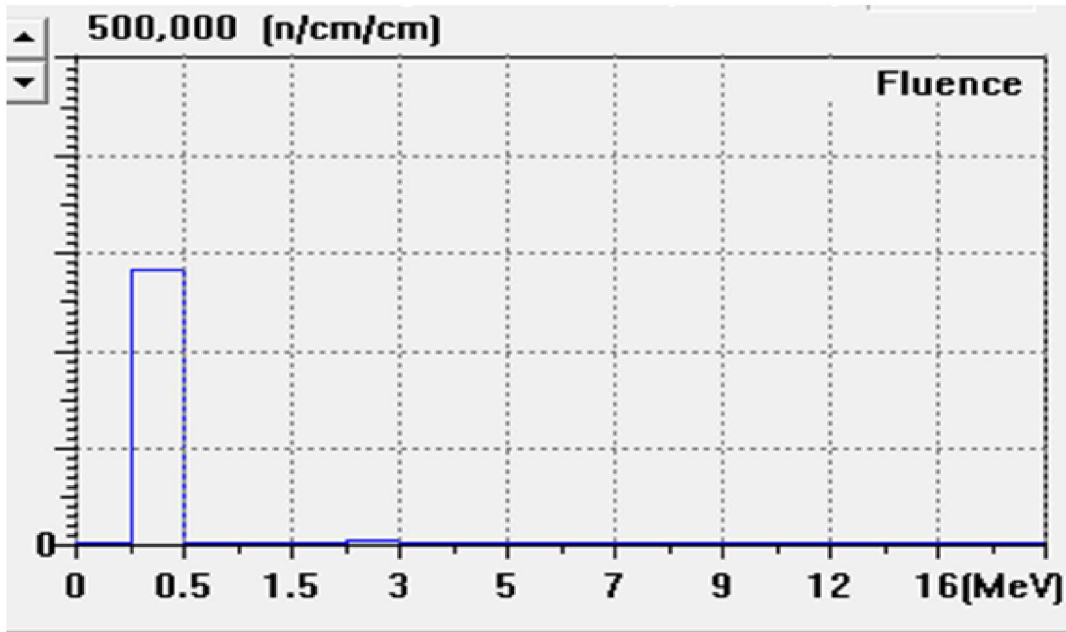


Figure 3: Measured neutron fluence spectrum at implanter control console, 30 May 2018. Average neutron dose rate was 2.43 mrem/h and the total integrated neutron dose was 3.97 mrem. The majority of the neutron fluence lies within the 0.01 to 0.5 MeV energy region. The measurement time was 1 hour, 37 minutes and 52 seconds.

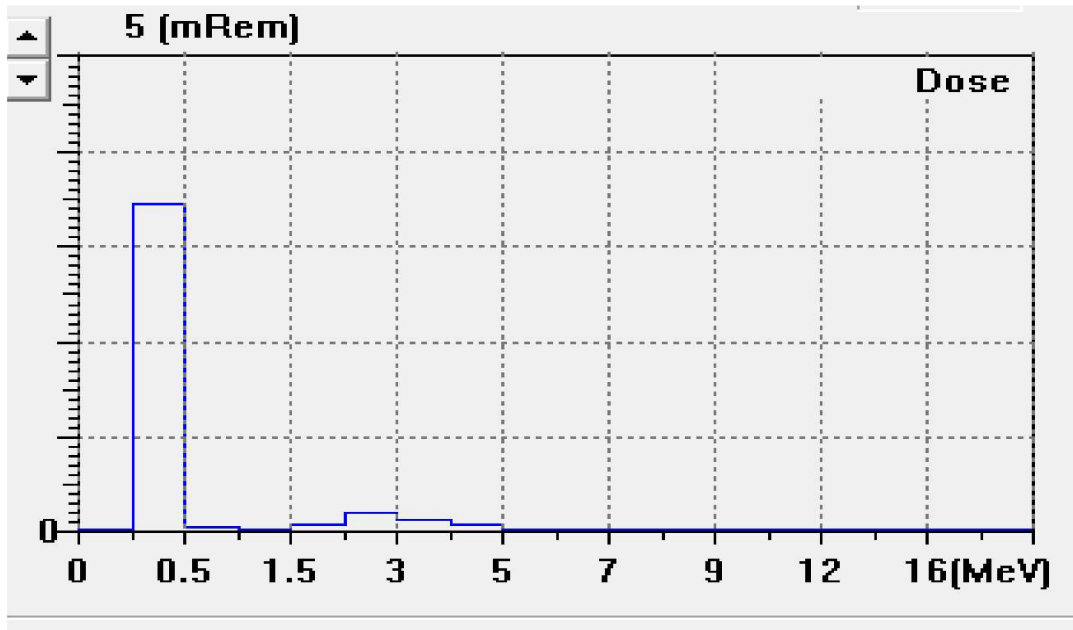


Figure 4: ICRP74 fluence-to-dose conversion factors have been applied to show the dose contributions by neutron energy interval. The implanter control console average neutron dose rate was 2.43 mrem/h and the total integrated neutron dose was 3.97 mrem.

Appendix A: Monitoring Data 30 May 2018; Implanter Control Console Area

PHOTON DATA

Application Version : Mobile Microspec V.6.8.2
File Name : C:\BTIData\May-30-2018\May-30-2018-Run-2\MAY-30-2018-RUN-2B-TOTAL.TXT
Run Number : 2
Time Run Started : May-30-2018 13:30:48
Time Data Exported : May-30-2018 15:07:12
Detector Channel : B
Probe Type : G 1.5x1.5
Duration (hh:mm:ss) : 01:37:16
Calibration Gain (keV/ch) : 12.39
Calibration Offset (ch) : 1.86
Count Rate (/s) : 490.4
Dead Time (%) : 3.92
Scaler Counts : 2859456
Comments : None

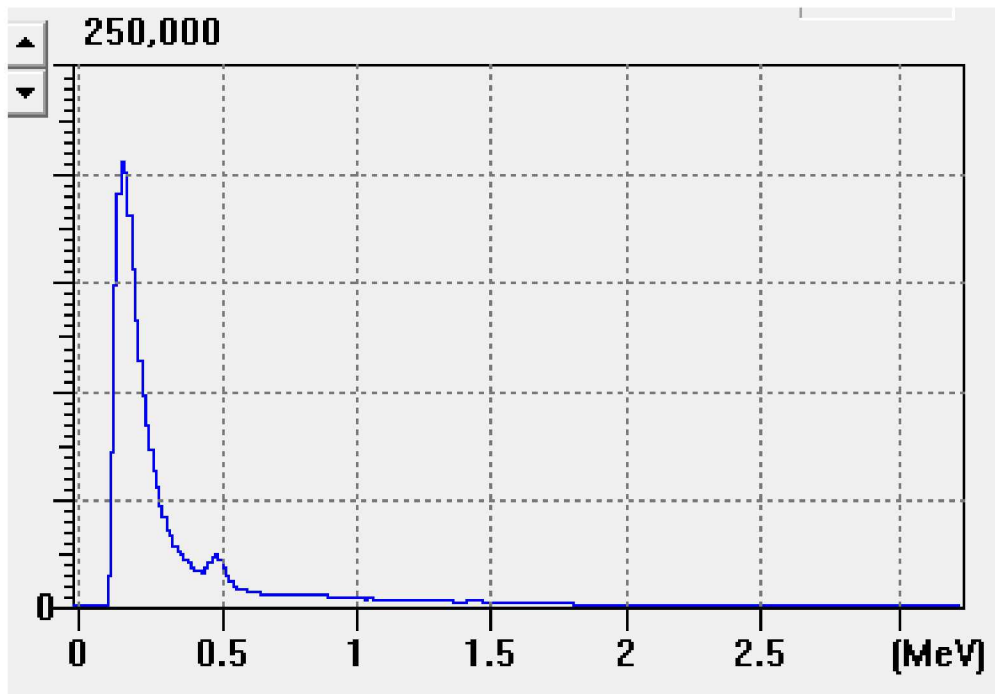


Figure 5: Photon energy spectrum measured at the implanter control console on 30 May 2018. The photon dose rate was 0.0542 mrem/h with a total photon dose over the measurement period of 0.0855 mrem. The Y axis shows counts per channel. The measured photon dose rate is elevated above the normal background range of 0.007 to 0.010 mrem/h.

Photon Monitoring Data
IBL, 30 May 2018
Location: Implanter Control Console

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
1	0	0	31	353	23637	61	735	5126
2	1	3	32	366	21928	62	748	5160
3	12	1	33	379	19919	63	760	5214
4	23	6	34	391	17991	64	773	5124
5	34	14	35	404	16703	65	786	5038
6	45	26	36	416	16143	66	799	5142
7	57	23	37	429	15962	67	812	5025
8	69	38	38	442	17346	68	825	5214
9	82	247	39	454	20163	69	838	5418
10	94	14778	40	467	23316	70	850	5236
11	106	71345	41	480	23570	71	863	5072
12	118	147355	42	492	21296	72	876	4945
13	130	190273	43	505	17829	73	889	4600
14	142	204658	44	518	14555	74	902	4476
15	155	199509	45	530	11578	75	915	4419
16	167	180168	46	543	9589	76	928	4288
17	179	155027	47	556	8407	77	941	4234
18	191	131662	48	569	7887	78	954	4185
19	204	112933	49	582	7581	79	966	4010
20	216	97619	50	595	7328	80	979	4024
21	229	83377	51	607	7071	81	992	3933
22	241	72231	52	620	6810	82	1005	3945
23	254	62746	53	633	6478	83	1018	3801
24	266	54408	54	645	6168	84	1031	3702
25	279	46491	55	658	6049	85	1044	3743
26	291	40878	56	671	5867	86	1057	3581
27	304	35278	57	684	5760	87	1070	3454
28	316	32337	58	696	5581	88	1083	3436
29	328	28248	59	709	5540	89	1096	3456
30	341	25614	60	722	5507	90	1109	3493

Photon Monitoring Data
IBL, 30 May 2018
Location: Implanter Control Console

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
91	1122	3466	121	1512	1920	151	1902	994
92	1135	3516	122	1525	1853	152	1915	968
93	1148	3304	123	1538	1814	153	1928	1031
94	1161	3306	124	1551	1766	154	1941	942
95	1174	3263	125	1564	1716	155	1954	922
96	1187	3288	126	1577	1672	156	1967	870
97	1200	3161	127	1590	1609	157	1979	821
98	1213	3070	128	1603	1624	158	1992	786
99	1227	3121	129	1616	1615	159	2005	828
100	1240	3025	130	1629	1596	160	2018	773
101	1253	2931	131	1642	1539	161	2031	776
102	1266	2875	132	1655	1508	162	2044	763
103	1279	2736	133	1668	1514	163	2057	730
104	1292	2649	134	1681	1418	164	2070	739
105	1305	2686	135	1694	1413	165	2083	737
106	1318	2541	136	1707	1467	166	2096	744
107	1331	2508	137	1720	1464	167	2109	734
108	1343	2523	138	1733	1429	168	2122	755
109	1356	2368	139	1746	1428	169	2134	768
110	1369	2429	140	1759	1433	170	2147	771
111	1382	2391	141	1772	1413	171	2160	793
112	1395	2393	142	1786	1287	172	2173	874
113	1408	2478	143	1799	1238	173	2186	844
114	1421	2507	144	1812	1153	174	2199	918
115	1434	2540	145	1825	1132	175	2212	911
116	1447	2654	146	1838	1110	176	2225	962
117	1460	2609	147	1851	1104	177	2238	806
118	1473	2393	148	1863	1061	178	2251	812
119	1486	2290	149	1876	1070	179	2264	689
120	1499	2144	150	1889	974	180	2277	677

Photon Monitoring Data
IBL, 30 May 2018
Location: Implanter Control Console

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
181	2290	638	211	2677	444	241	3056	427
182	2303	598	212	2690	463	242	3069	416
183	2316	596	213	2702	456	243	3082	422
184	2328	589	214	2715	441	244	3094	345
185	2341	592	215	2728	480	245	3107	394
186	2354	541	216	2740	456	246	3119	396
187	2367	581	217	2753	473	247	3132	328
188	2380	553	218	2766	463	248	3145	351
189	2393	575	219	2778	454	249	3157	383
190	2406	578	220	2791	476	250	3170	378
191	2419	521	221	2804	448	251	3183	380
192	2432	515	222	2816	397	252	3195	373
193	2445	556	223	2829	443	253	3208	367
194	2458	530	224	2842	415	254	3220	368
195	2471	548	225	2854	394			
196	2484	582	226	2867	435			
197	2497	519	227	2880	410			
198	2510	547	228	2892	412			
199	2523	547	229	2905	411			
200	2536	514	230	2917	477			
201	2549	532	231	2930	410			
202	2562	551	232	2943	438			
203	2575	561	233	2955	439			
204	2588	570	234	2968	391			
205	2601	549	235	2981	420			
206	2614	514	236	2993	419			
207	2626	535	237	3006	400			
208	2639	518	238	3019	395			
209	2652	460	239	3031	362			
210	2664	490	240	3044	400			

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APPENDIX B: MONITORING DATA: ROOM 106, VISITOR TLD BADGE STORAGE AREA



Figure 6: Visitor badge storage location in room 106.

Monitoring Data 30 May 2018; Room 106, Visitor TLD Storage Area

NEUTRON DATA:

Application Version : Mobile Microspec V.6.8.2
 File Name : C:\BTIDData\May-30-2018\May-30-2018-Run-2\May-30-2018-Run-3\MAY-30-2018-RUN-3A-TOTAL.TXT
 Run Number : 2
 Time Run Started : May-30-2018 15:26:40
 Time Data Exported : Jul-03-2018 16:29:58
 Detector Channel : A
 Probe Type : N 2x2
 Duration (hh:mm:ss) : 17:14:28
 Calibration Gain (keV/ch) : [Hi-Gain] 4.92 ; [Lo-Gain] 51.01 ; [3He] 10.19
 Calibration Offset (ch) : [Hi-Gain] 0.00 ; [Lo-Gain] 0.00 ; [3He] 0.00
 Count Rate (/s) : [NE213] 1.0 ; [3He] 0.0
 Dead Time (%) : 2.07
 Scaler Counts : [Fast N] 60957; [Gamma] 1477434; [3He] 1763
 Comments : None

UNFOLDED NEUTRON SPECTRUM

Emin (MeV)	Emax (MeV)	Fluence (1/cm2)	Dose (mrem)	Flux (1/cm2/s)	Dose Rate (mrem/h)
0	0.01	1601.092	0.002	0.026	0
0.01	0.5	191314.462	2.335	3.082	0.135
0.5	1	1018.044	0.044	0.016	0.003
1	1.5	135.968	0.007	0.002	0
1.5	2	1090.222	0.052	0.018	0.003
2	3	3953.222	0.184	0.064	0.011
3	4	1423.991	0.073	0.023	0.004
4	5	1753.886	0.083	0.028	0.005
5	6	700.252	0.03	0.011	0.002
6	7	623.291	0.026	0.01	0.002
7	8	243.814	0.01	0.004	0.001
8	9	158.87	0.007	0.003	0
9	10	6.605	0	0	0
10	12	5.149	0	0	0
12	14	29.333	0.001	0	0
14	16	-5.1	0	0	0
16	18	-10.706	-0.001	0	0
18	20	43.942	0.002	0.001	0
Total		204086.339	2.856	3.288	0.166

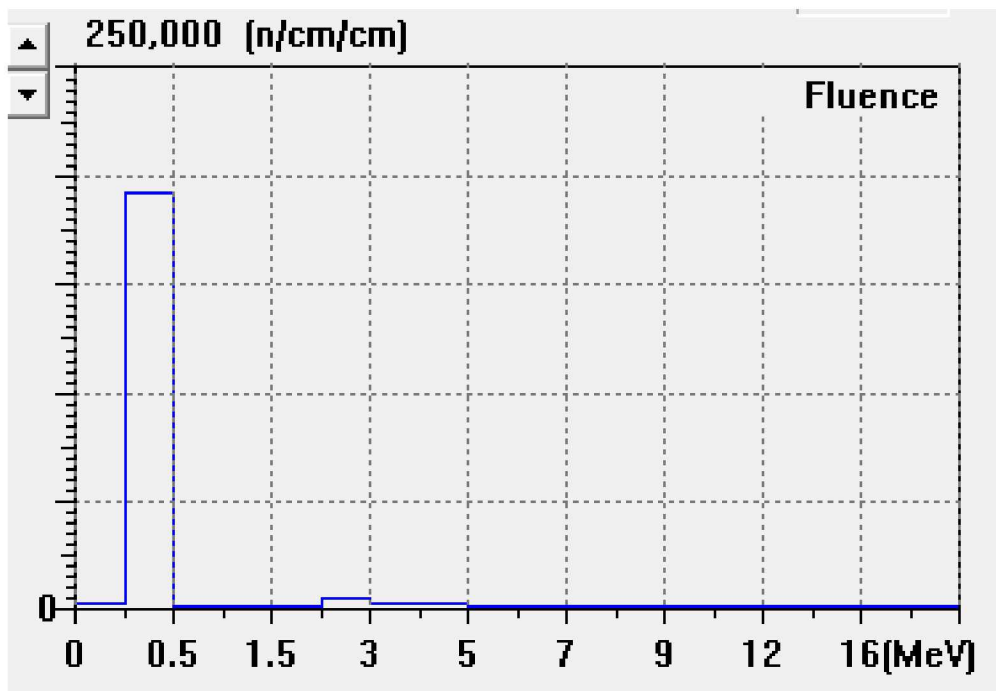


Figure 7: Neutron spectral data taken in Bldg. 720, Room 106, beginning at 15:26 on 30 May 2018. This room contains the TLD storage rack for visitor TLD badges.

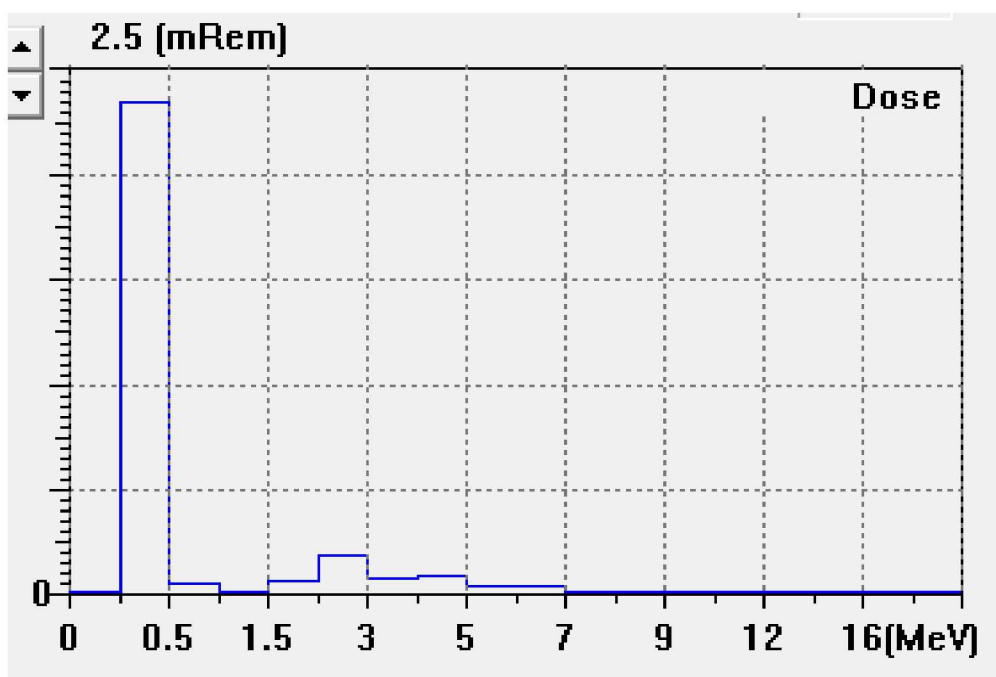


Figure 8: Data taken in Bldg. 720, Room 106, beginning at 15:26 on 30 May 2018. ICRP74 fluence -to-dose equivalent conversion factors were applied to show the dose contribution by energy region. This data indicates that during target irradiation, the badge storage location was receiving 0.166 mrem/h from neutron radiation.

B: Monitoring Data 30 May 2018; Room 106, Visitor TLD Badge Storage Location

PHOTON DATA

Application Version : Mobile Microspec V.6.8.2
File Name : C:\BTIData\May-30-2018\May-30-2018-Run-2\May-30-2018-Run-3\MAY-30-2018-RUN-3B-TOTAL.TXT
Run Number : 2
Time Run Started : May-30-2018 15:26:40
Time Data Exported : Jul-03-2018 16:29:59
Detector Channel : B
Probe Type : G 1.5x1.5
Duration (hh:mm:ss) : 17:14:28
Calibration Gain (keV/ch) : 12.43
Calibration Offset (ch) : 2.04
Count Rate (/s) : 70.8
Dead Time (%) : 1.64
Scaler Counts : 4391653
Comments : None

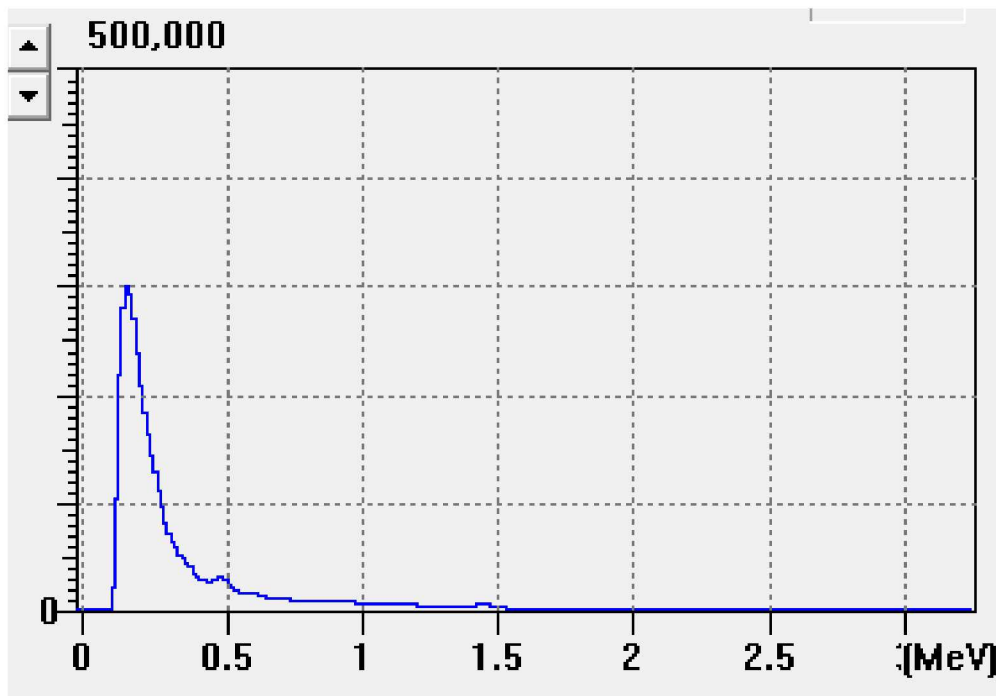


Figure 9: Photon spectrum taken in Bldg. 720, Room 106, beginning at 15:26 on 30 May 2018. Data was collected for 17 h, 14 min and 28 s. The average measured dose rate of 0.0074 mrem/h is consistent with normal environmental gamma radiation levels. This data indicates that there is no increase in gamma radiation levels above normal background during target irradiation, at the visitor badge storage location.

Photon Monitoring Data
IBL, 30 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
1	0	0	31	352	44090	61	735	9693
2	0	0	32	365	39718	62	748	9602
3	10	0	33	377	34602	63	760	9452
4	21	0	34	390	31345	64	773	9222
5	32	0	35	403	29176	65	786	8786
6	43	0	36	415	27572	66	799	8780
7	55	0	37	428	26534	67	812	8494
8	67	2290	38	441	26735	68	825	8496
9	80	299	39	453	28995	69	838	8267
10	92	20821	40	466	30308	70	851	8162
11	104	103274	41	479	29970	71	864	7979
12	116	216234	42	491	27324	72	877	8128
13	128	278609	43	504	24189	73	890	7937
14	140	299037	44	517	21368	74	902	7926
15	153	290605	45	530	18390	75	915	7987
16	165	267756	46	543	16788	76	928	7654
17	177	236029	47	555	16135	77	941	7537
18	190	207626	48	568	16461	78	954	7469
19	202	182234	49	581	16423	79	967	7124
20	215	162548	50	594	16454	80	980	6872
21	227	143357	51	607	15495	81	993	6526
22	240	126985	52	620	14297	82	1006	6283
23	252	109718	53	632	12742	83	1019	6192
24	265	95126	54	645	11811	84	1032	6085
25	277	81198	55	658	11083	85	1045	6026
26	290	71693	56	671	10784	86	1058	6019
27	302	63447	57	683	10325	87	1071	5895
28	315	57671	58	696	10120	88	1084	6081
29	327	51817	59	709	10197	89	1097	6151
30	340	47901	60	722	9967	90	1110	6037

Photon Monitoring Data
IBL, 30 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
91	1123	6068	121	1514	2568	151	1905	1067
92	1136	5944	122	1527	2190	152	1918	1081
93	1149	5733	123	1540	2075	153	1931	993
94	1162	5644	124	1553	2147	154	1944	1043
95	1175	5397	125	1566	2132	155	1957	997
96	1189	5277	126	1579	1955	156	1970	937
97	1202	4821	127	1592	1932	157	1983	927
98	1215	4540	128	1605	1826	158	1996	862
99	1228	4321	129	1618	1719	159	2009	895
100	1241	4211	130	1631	1726	160	2022	867
101	1254	3965	131	1644	1622	161	2035	890
102	1267	3734	132	1658	1672	162	2048	874
103	1280	3545	133	1671	1647	163	2061	907
104	1293	3411	134	1684	1644	164	2074	952
105	1306	3387	135	1697	1624	165	2087	913
106	1319	3222	136	1710	1662	166	2100	946
107	1332	3156	137	1723	1749	167	2113	981
108	1345	3113	138	1736	1700	168	2125	922
109	1358	3284	139	1749	1672	169	2138	924
110	1371	3346	140	1762	1707	170	2151	994
111	1384	3735	141	1775	1521	171	2164	1003
112	1397	4152	142	1789	1482	172	2177	1009
113	1410	4940	143	1802	1384	173	2190	954
114	1423	5525	144	1815	1332	174	2203	910
115	1436	6134	145	1828	1272	175	2216	944
116	1449	6090	146	1841	1242	176	2229	873
117	1462	5787	147	1854	1190	177	2242	862
118	1475	4751	148	1867	1145	178	2255	821
119	1488	4010	149	1880	1120	179	2268	757
120	1501	3076	150	1893	1098	180	2281	715

Photon Monitoring Data
IBL, 30 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
181	2294	709	211	2683	391	241	3063	302
182	2307	683	212	2695	383	242	3076	337
183	2320	657	213	2708	414	243	3088	318
184	2333	641	214	2721	406	244	3101	334
185	2346	574	215	2733	387	245	3114	329
186	2359	617	216	2746	389	246	3126	358
187	2372	582	217	2759	407	247	3139	320
188	2385	538	218	2771	371	248	3152	341
189	2398	575	219	2784	369	249	3164	329
190	2411	550	220	2797	372	250	3177	311
191	2424	492	221	2810	374	251	3189	314
192	2437	547	222	2822	368	252	3202	297
193	2450	553	223	2835	330	253	3215	315
194	2463	501	224	2848	352	254	3227	341
195	2476	509	225	2860	353			
196	2489	526	226	2873	385			
197	2502	496	227	2886	357			
198	2515	582	228	2898	382			
199	2528	621	229	2911	357			
200	2541	708	230	2924	294			
201	2554	759	231	2936	344			
202	2567	722	232	2949	318			
203	2580	764	233	2962	327			
204	2593	739	234	2974	372			
205	2606	679	235	2987	311			
206	2619	681	236	3000	365			
207	2632	590	237	3012	357			
208	2645	530	238	3025	329			
209	2657	449	239	3038	369			
210	2670	458	240	3050	337			

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APPENDIX C: MONITORING DATA: COMPUTER WORK STATION IN LIMITED AREA

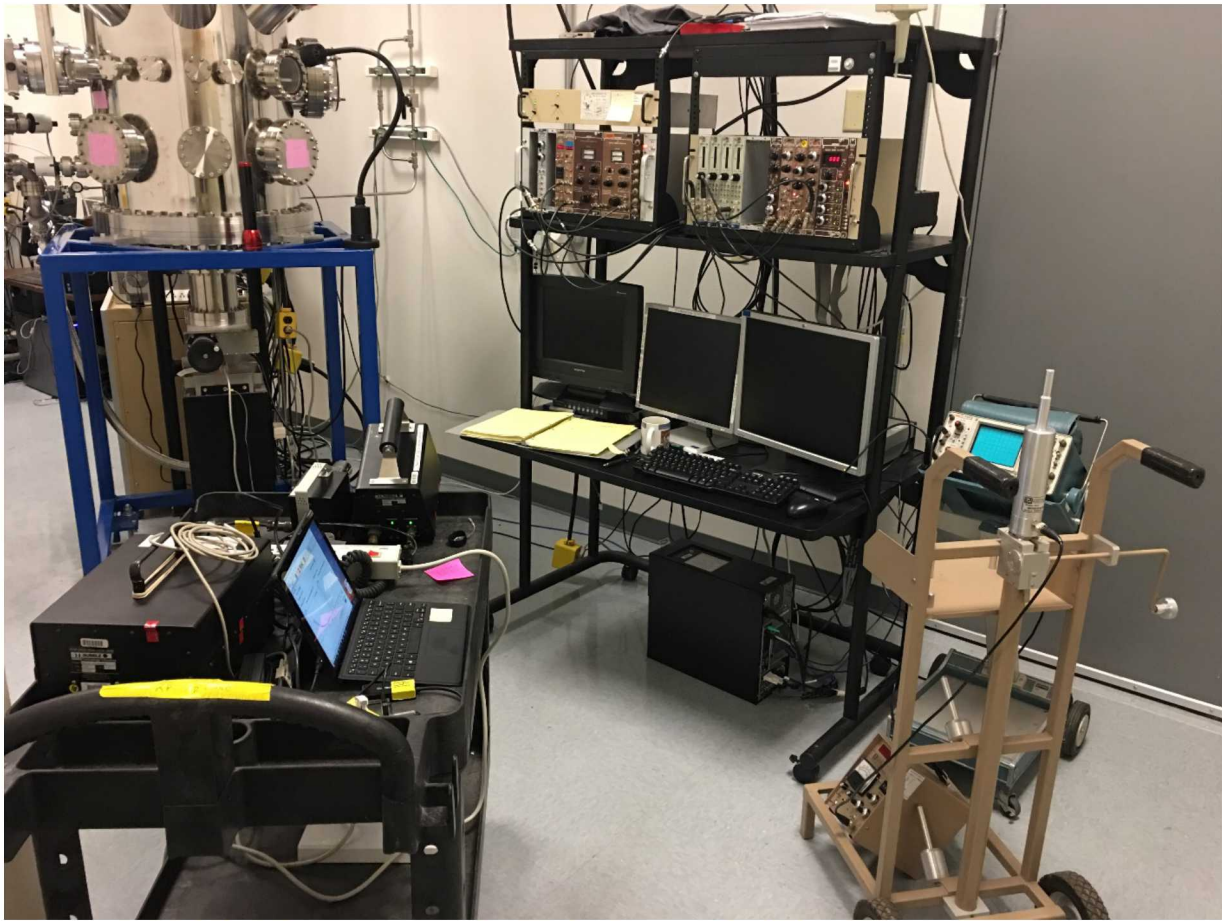


Figure 10: Mobile Microspec set-up in Limited Area of building 720.

C: Monitoring Data 31 May 2018; Computer Work Station in Limited Area

NEUTRON DATA:

Application Version : Mobile Microspec V.6.8.2
 File Name : C:\BTIData\May-31-2018\May-31-2018-Run-3\MAY-31-2018-RUN-3A-TOTAL.TXT
 Run Number : 2
 Time Run Started : May-31-2018 09:37:09
 Time Data Exported : May-31-2018 12:29:09
 Detector Channel : A
 Probe Type : N 2x2
 Duration (hh:mm:ss) : 02:54:15
 Calibration Gain (keV/ch) : [Hi-Gain] 4.97 ; [Lo-Gain] 51.20 ; [3He] 10.19
 Calibration Offset (ch) : [Hi-Gain] 0.00 ; [Lo-Gain] 0.00 ; [3He] 0.00
 Count Rate (/s) : [NE213] 8.5 ; [3He] 0.2
 Dead Time (%) : 4.14
 Scaler Counts : [Fast N] 82654; [Gamma] 1011267; [3He] 2448
 Comments : None

UNFOLDED NEUTRON SPECTRUM

Emin (MeV)	Emax (MeV)	Fluence (1/cm2)	Dose (mrem)	Flux (1/cm2/s)	Dose Rate (mrem/h)
0	0.01	801.148	0.001	0.077	0
0.01	0.5	289599.555	3.535	27.7	1.217
0.5	1	-4206.785	-0.181	-0.402	-0.062
1	1.5	885.408	0.044	0.085	0.015
1.5	2	1992.308	0.095	0.191	0.033
2	3	5549.869	0.258	0.531	0.089
3	4	2163.605	0.11	0.207	0.038
4	5	1546.755	0.073	0.148	0.025
5	6	842.929	0.037	0.081	0.013
6	7	577.952	0.024	0.055	0.008
7	8	321.487	0.013	0.031	0.005
8	9	195.871	0.008	0.019	0.003
9	10	86.409	0.004	0.008	0.001
10	12	22.531	0.001	0.002	0
12	14	-0.395	0	0	0
14	16	-1.069	0	0	0
16	18	-4.463	0	0	0
18	20	7.479	0	0.001	0
Total:		300380.594	4.022	28.731	1.385

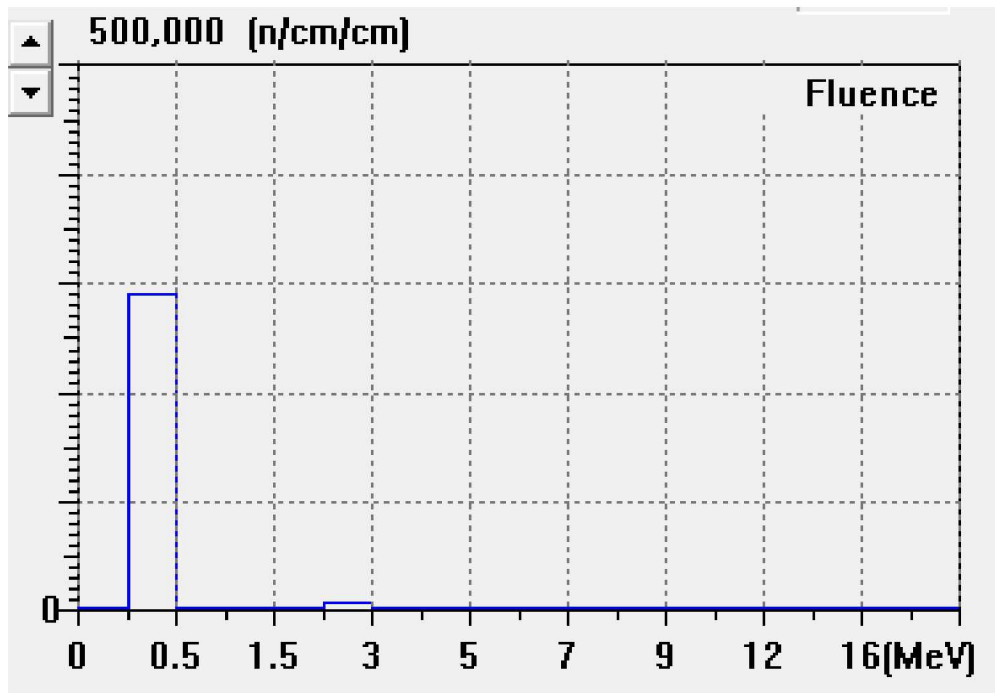


Figure 11: Neutron fluence measurement results in the IBL Limited Area.

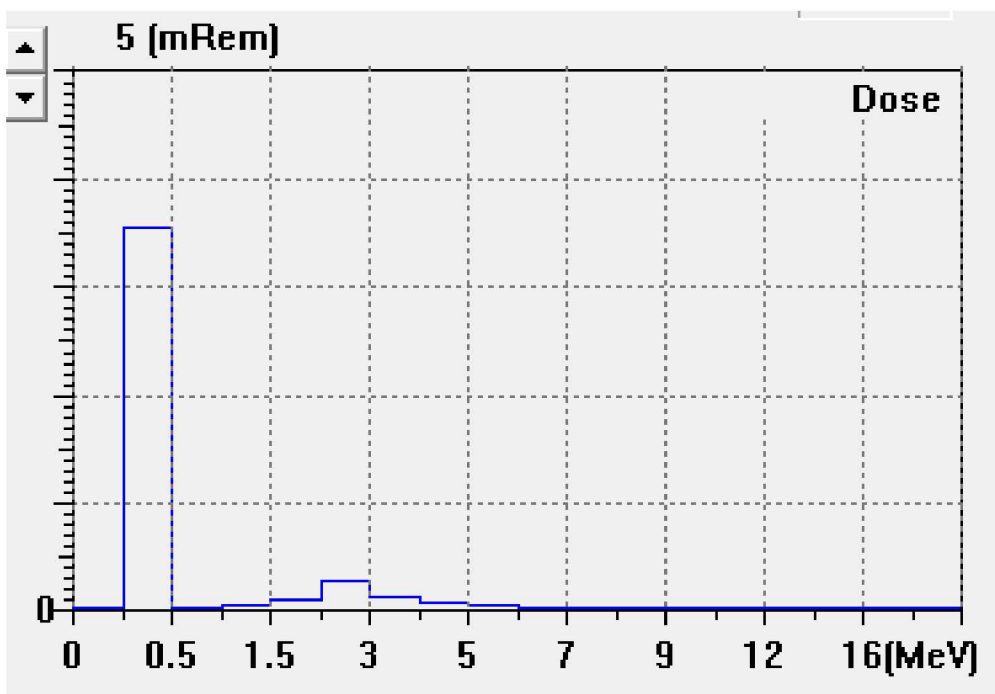


Figure 12: ICRP 74 fluence-to-dose conversion factors were applied to the fluence spectrum shown in Figure 10.

C: Monitoring Data 31 May 2018; Computer Work Station in Limited Area

PHOTON DATA

Application Version : Mobile Microspec V.6.8.2
File Name : C:\BTIData\May-31-2018\May-31-2018-Run-3\MAY-31-2018-RUN-3B-TOTAL.TXT
Run Number : 2
Time Run Started : May-31-2018 09:37:09
Time Data Exported : May-31-2018 12:29:09
Detector Channel : B
Probe Type : G 1.5x1.5
Duration (hh:mm:ss) : 02:54:21
Calibration Gain (keV/ch) : 12.45
Calibration Offset (ch) : 2.06
Count Rate (/s) : 273.3
Dead Time (%) : 2.80
Scaler Counts : 2857563
Comments : None

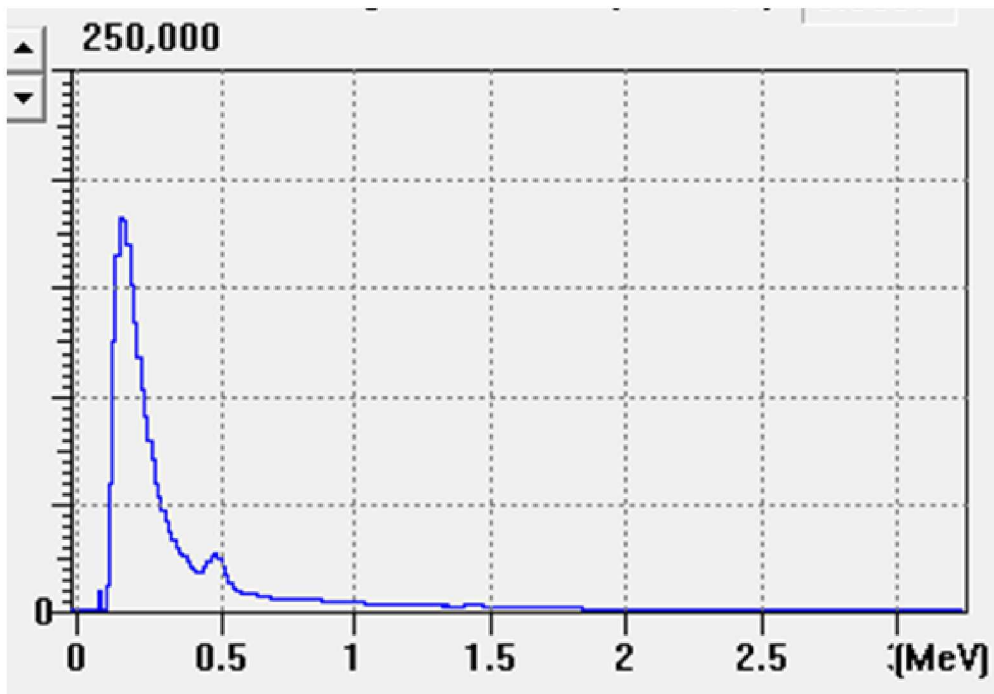


Figure 13: Measured photon spectrum by Computer Work Station in IBL Limited Area

Photon Monitoring Data
IBL Computer Work Station in Limited Area, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
1	0	0	31	353	27124	61	736	5546
2	0	1	32	365	25429	62	749	5484
3	10	0	33	378	22522	63	762	5488
4	21	0	34	391	20797	64	774	5209
5	32	0	35	403	19207	65	787	5467
6	43	2	36	416	18146	66	800	5325
7	55	2	37	428	18273	67	813	5344
8	67	8691	38	441	19997	68	826	5646
9	80	208	39	454	23228	69	839	5540
10	92	11926	40	467	25689	70	852	5435
11	104	58999	41	479	26662	71	865	5162
12	116	124256	42	492	24263	72	878	4854
13	128	163943	43	505	20305	73	891	4643
14	141	180893	44	518	16702	74	904	4574
15	153	180381	45	531	12922	75	917	4396
16	165	169455	46	543	10665	76	930	4416
17	178	150017	47	556	9229	77	943	4200
18	190	132493	48	569	8839	78	956	4152
19	202	116572	49	582	8320	79	969	4121
20	215	102621	50	595	8267	80	982	4053
21	227	89208	51	608	7755	81	994	3875
22	240	78946	52	620	7517	82	1007	3888
23	252	69369	53	633	6983	83	1020	3793
24	265	59140	54	646	6811	84	1033	3650
25	278	52409	55	659	6344	85	1046	3658
26	290	46192	56	672	6230	86	1060	3582
27	303	40899	57	684	6067	87	1073	3523
28	315	36608	58	697	5852	88	1086	3558
29	328	32670	59	710	5825	89	1099	3579
30	340	29450	60	723	5814	90	1112	3503

Photon Monitoring Data
IBL Computer Work Station in Limited Area, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
91	1125	3444	121	1516	1971	151	1908	1103
92	1138	3419	122	1529	1792	152	1921	1086
93	1151	3342	123	1542	1862	153	1934	1115
94	1164	3389	124	1556	1777	154	1947	1059
95	1177	3317	125	1569	1720	155	1960	995
96	1190	3291	126	1582	1731	156	1973	987
97	1204	3252	127	1595	1643	157	1986	967
98	1217	3075	128	1608	1750	158	1999	898
99	1230	3138	129	1621	1596	159	2012	910
100	1243	2999	130	1634	1650	160	2025	865
101	1256	2872	131	1647	1613	161	2038	911
102	1269	2797	132	1660	1584	162	2051	861
103	1282	2722	133	1673	1547	163	2064	911
104	1295	2618	134	1686	1593	164	2077	874
105	1308	2494	135	1699	1470	165	2090	854
106	1321	2434	136	1713	1553	166	2103	835
107	1334	2506	137	1726	1566	167	2116	878
108	1347	2469	138	1739	1441	168	2129	823
109	1360	2342	139	1752	1397	169	2142	886
110	1373	2362	140	1765	1411	170	2155	943
111	1386	2388	141	1778	1467	171	2168	919
112	1399	2535	142	1791	1378	172	2181	901
113	1412	2566	143	1805	1384	173	2194	996
114	1425	2646	144	1818	1295	174	2207	972
115	1438	2799	145	1831	1250	175	2220	1012
116	1451	2661	146	1844	1212	176	2233	901
117	1464	2595	147	1857	1181	177	2246	925
118	1477	2458	148	1870	1121	178	2259	822
119	1490	2297	149	1883	1105	179	2272	753
120	1503	2057	150	1896	1129	180	2285	785

Photon Monitoring Data
IBL Computer Work Station in Limited Area, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
181	2298	715	211	2687	591	241	3068	478
182	2311	726	212	2700	581	242	3080	458
183	2324	734	213	2712	580	243	3093	424
184	2337	675	214	2725	567	244	3106	471
185	2350	646	215	2738	550	245	3119	473
186	2363	681	216	2750	568	246	3131	496
187	2376	677	217	2763	553	247	3144	434
188	2389	629	218	2776	570	248	3157	436
189	2402	627	219	2789	550	249	3169	442
190	2415	661	220	2801	562	250	3182	476
191	2428	685	221	2814	526	251	3195	476
192	2441	646	222	2827	521	252	3207	451
193	2454	670	223	2839	514	253	3220	447
194	2467	666	224	2852	506	254	3233	415
195	2480	642	225	2865	500			
196	2493	635	226	2877	489			
197	2506	665	227	2890	477			
198	2519	650	228	2903	495			
199	2532	646	229	2916	491			
200	2545	649	230	2928	521			
201	2558	594	231	2941	508			
202	2571	648	232	2954	518			
203	2584	658	233	2966	487			
204	2597	585	234	2979	490			
205	2610	617	235	2992	448			
206	2623	639	236	3004	491			
207	2636	590	237	3017	472			
208	2649	581	238	3030	503			
209	2661	555	239	3042	490			
210	2674	595	240	3055	437			

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APPENDIX D: MONITORING DATA: BEHIND SHIELD WALL FOR TANDEM ACCELERATOR

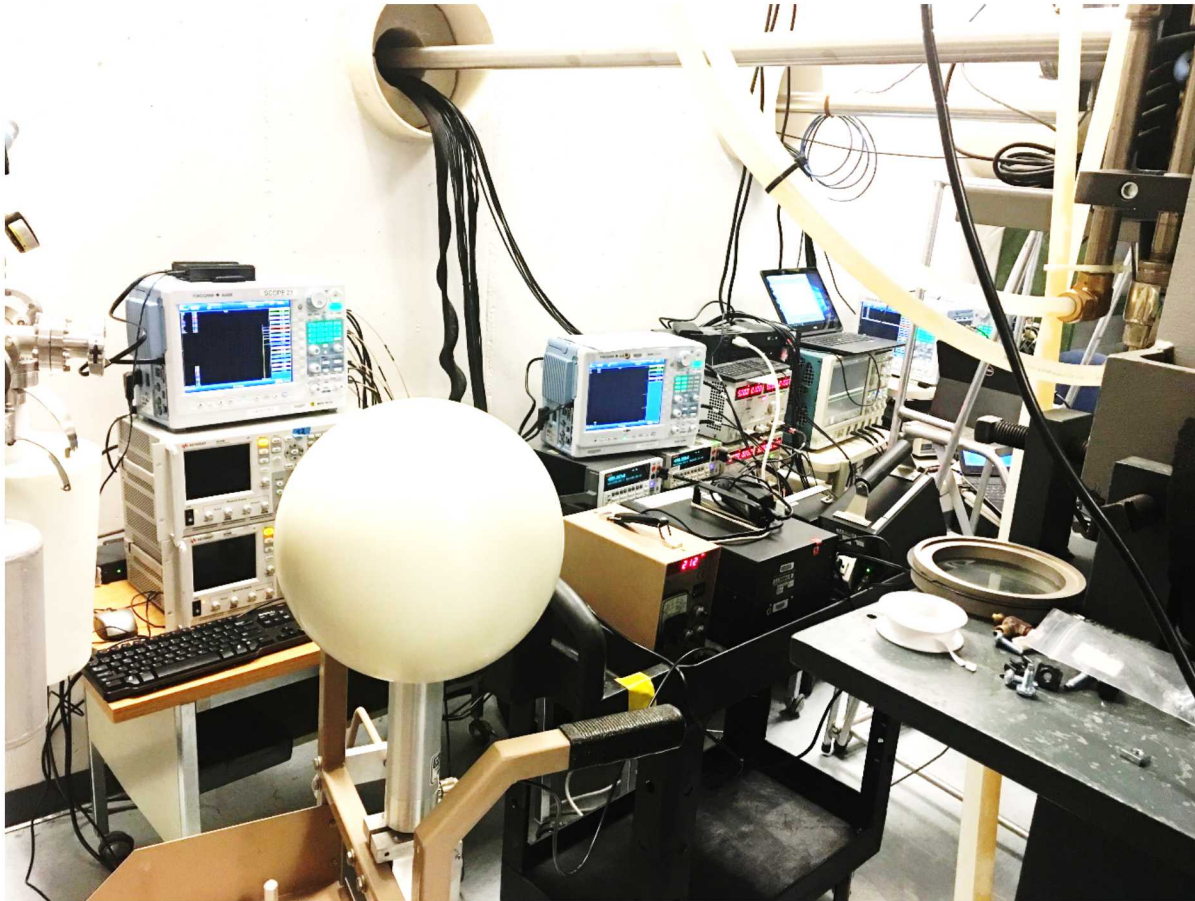


Figure 14: Monitoring location behind Tandem shield wall.

D: Monitoring Data 31 May 2018; Computer Work Station Behind Shield Wall for Tandem Accelerator

NEUTRON DATA:

Application Version : Mobile Microspec V.6.8.2
 File Name : C:\BTIData\May-31-2018\May-31-2018-Run-4\MAY-31-2018-RUN-4A-TOTAL.TXT
 Run Number : 3
 Time Run Started : May-31-2018 12:54:04
 Time Data Exported : May-31-2018 16:12:05
 Detector Channel : A
 Probe Type : N 2x2
 Duration (hh:mm:ss) : 03:15:53
 Calibration Gain (keV/ch) : [Hi-Gain] 4.97 ; [Lo-Gain] 51.20 ; [3He] 10.19
 Calibration Offset (ch) : [Hi-Gain] 0.00 ; [Lo-Gain] 0.00 ; [3He] 0.00
 Count Rate (/s) : [NE213] 8.6 ; [3He] 0.3
 Dead Time (%) : 4.31
 Scaler Counts : [Fast N] 93057; [Gamma] 1514527; [3He] 3779
 Comments : None

UNFOLDED NEUTRON SPECTRUM

Emin (MeV)	Emax (MeV)	Fluence (1/cm2)	Dose (mrem)	Flux (1/cm2/s)	Dose Rate (mrem/h)
0	0.01	1839.317	0.002	0.156	0.001
0.01	0.5	448428.782	5.473	38.154	1.676
0.5	1	2324.281	0.1	0.198	0.031
1	1.5	1073.438	0.053	0.091	0.016
1.5	2	2217.335	0.106	0.189	0.032
2	3	6595.691	0.307	0.561	0.094
3	4	2288.701	0.117	0.195	0.036
4	5	1888.951	0.09	0.161	0.027
5	6	1009.153	0.044	0.086	0.013
6	7	705.972	0.029	0.06	0.009
7	8	431.205	0.018	0.037	0.005
8	9	110.529	0.005	0.009	0.001
9	10	-0.739	0	0	0
10	12	13.761	0.001	0.001	0
12	14	7.695	0	0.001	0
14	16	0.319	0	0	0
16	18	20.255	0.001	0.002	0
18	20	-1.113	0	0	0
Total:		468953.531	6.345	39.901	1.944

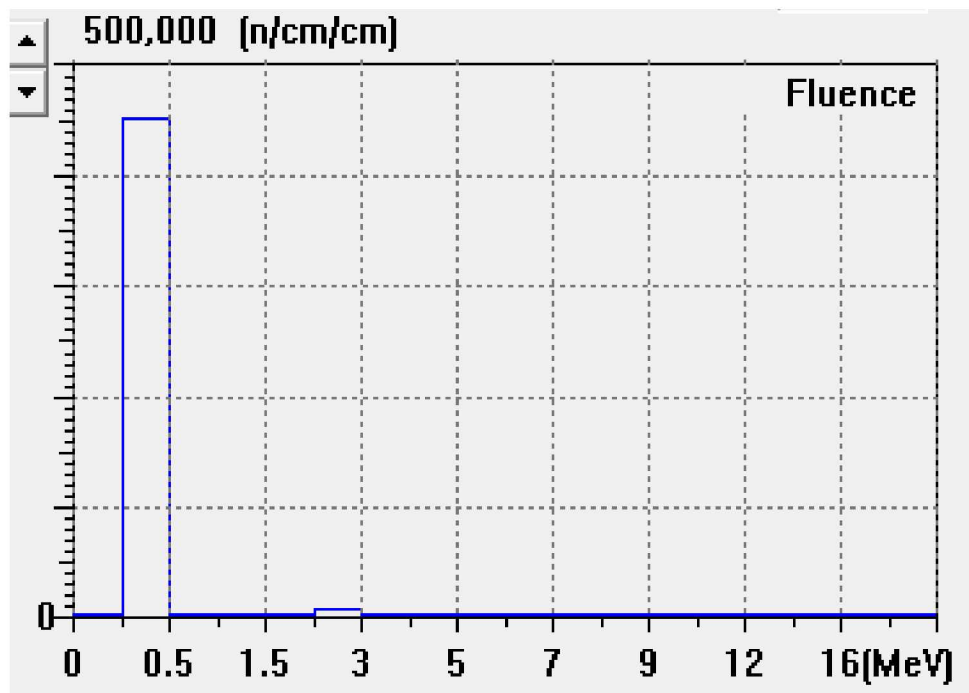


Figure 15: Measured neutron fluence behind the Tandem Shield Wall

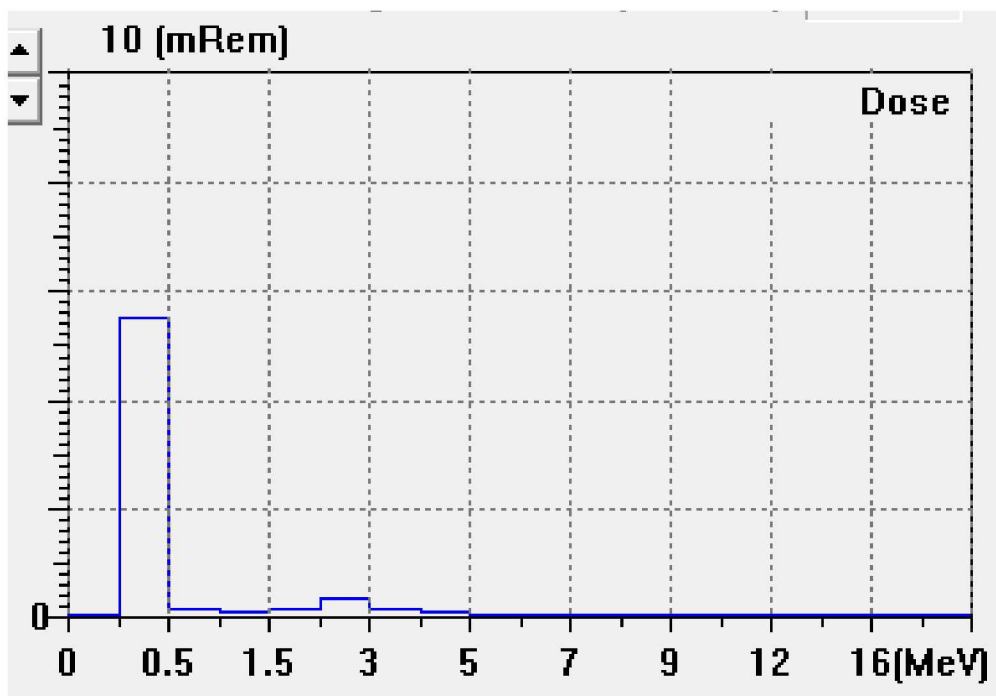


Figure 16: ICRP 74 fluence to dose equivalent conversion factors were applied to the spectrum shown in Figure 12.

D: Monitoring Data 31 May 2018; Computer Work Station Behind Shield Wall for Tandem
Accelerator

PHOTON DATA

Application Version : Mobile Microspec V.6.8.2
File Name : C:\BTIDData\May-31-2018\May-31-2018-Run-4\MAY-31-2018-
RUN-4B-TOTAL.TXT
Run Number : 3
Time Run Started : May-31-2018 12:54:04
Time Data Exported : May-31-2018 16:12:05
Detector Channel : B
Probe Type : G 1.5x1.5
Duration (hh:mm:ss) : 03:15:53
Calibration Gain (keV/ch) : 12.45
Calibration Offset (ch) : 2.06
Count Rate (/s) : 394.5
Dead Time (%) : 3.09
Scaler Counts : 4633703
Comments : None

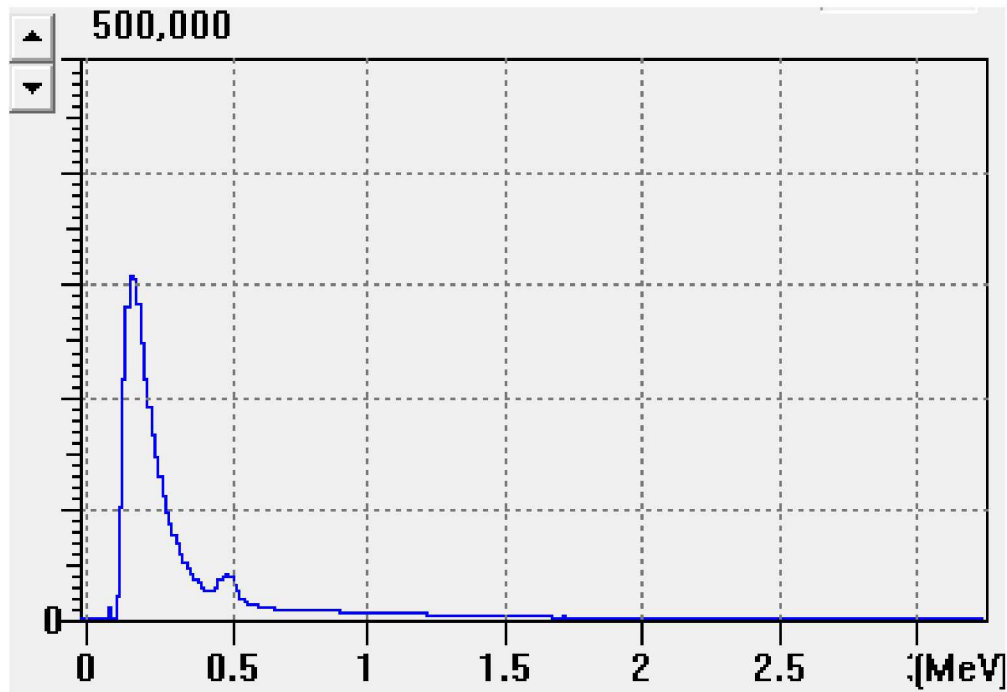


Figure 17: Measured photon spectrum behind the Tandem shield wall.

Photon Monitoring Data
IBL Behind The Tandem Shield Wall, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
1	0	0	31	353	40507	61	736	8631
2	0	2	32	365	36680	62	749	8599
3	10	0	33	378	32814	63	762	8697
4	21	3	34	391	29593	64	774	8565
5	32	0	35	403	26867	65	787	8628
6	43	3	36	416	25598	66	800	8459
7	55	9	37	428	25818	67	813	8485
8	67	10395	38	441	28722	68	826	8657
9	80	315	39	454	34848	69	839	8481
10	92	20421	40	467	39470	70	852	8205
11	104	100653	41	479	40872	71	865	8107
12	116	212951	42	492	37151	72	878	7839
13	128	278997	43	505	31417	73	891	7173
14	141	304943	44	518	25189	74	904	7091
15	153	302009	45	531	19499	75	917	6896
16	165	280191	46	543	16041	76	930	6987
17	178	246749	47	556	14098	77	943	6649
18	190	214935	48	569	13239	78	956	6619
19	202	189659	49	582	12473	79	969	6531
20	215	165552	50	595	12241	80	982	6398
21	227	144222	51	608	11725	81	994	6189
22	240	127039	52	620	11236	82	1007	6095
23	252	111078	53	633	10566	83	1020	5888
24	265	96254	54	646	10532	84	1033	5898
25	278	85504	55	659	9722	85	1046	5704
26	290	75499	56	672	9720	86	1060	5603
27	303	67333	57	684	9557	87	1073	5694
28	315	59393	58	697	9237	88	1086	5578
29	328	51510	59	710	9057	89	1099	5618
30	340	45533	60	723	8974	90	1112	5587

Photon Monitoring Data
IBL Behind The Tandem Shield Wall, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
91	1125	5705	121	1516	3162	151	1908	1831
92	1138	5731	122	1529	3013	152	1921	1780
93	1151	5607	123	1542	2858	153	1934	1776
94	1164	5346	124	1556	2993	154	1947	1802
95	1177	5385	125	1569	2867	155	1960	1687
96	1190	5232	126	1582	2738	156	1973	1628
97	1204	5128	127	1595	2784	157	1986	1635
98	1217	4845	128	1608	2748	158	1999	1555
99	1230	4709	129	1621	2739	159	2012	1502
100	1243	4657	130	1634	2663	160	2025	1482
101	1256	4563	131	1647	2626	161	2038	1388
102	1269	4420	132	1660	2545	162	2051	1361
103	1282	4332	133	1673	2449	163	2064	1398
104	1295	4272	134	1686	2414	164	2077	1392
105	1308	3946	135	1699	2475	165	2090	1375
106	1321	3969	136	1713	2513	166	2103	1378
107	1334	4064	137	1726	2457	167	2116	1365
108	1347	4079	138	1739	2409	168	2129	1403
109	1360	3939	139	1752	2342	169	2142	1427
110	1373	3881	140	1765	2293	170	2155	1463
111	1386	3943	141	1778	2281	171	2168	1545
112	1399	3948	142	1791	2276	172	2181	1541
113	1412	4109	143	1805	2103	173	2194	1588
114	1425	4127	144	1818	2019	174	2207	1539
115	1438	4418	145	1831	1961	175	2220	1545
116	1451	4366	146	1844	1963	176	2233	1462
117	1464	4242	147	1857	1880	177	2246	1429
118	1477	4067	148	1870	1832	178	2259	1347
119	1490	3669	149	1883	1823	179	2272	1303
120	1503	3381	150	1896	1890	180	2285	1229

Photon Monitoring Data
IBL Behind The Tandem Shield Wall, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
181	2298	1171	211	2687	960	241	3068	772
182	2311	1129	212	2700	889	242	3080	721
183	2324	1151	213	2712	906	243	3093	832
184	2337	1163	214	2725	872	244	3106	752
185	2350	1175	215	2738	906	245	3119	734
186	2363	1125	216	2750	924	246	3131	735
187	2376	1065	217	2763	908	247	3144	752
188	2389	1116	218	2776	917	248	3157	773
189	2402	1047	219	2789	936	249	3169	724
190	2415	1090	220	2801	930	250	3182	782
191	2428	1039	221	2814	876	251	3195	717
192	2441	1037	222	2827	845	252	3207	751
193	2454	1042	223	2839	853	253	3220	728
194	2467	1063	224	2852	849	254	3233	692
195	2480	1107	225	2865	844			
196	2493	1067	226	2877	777			
197	2506	1055	227	2890	830			
198	2519	1035	228	2903	782			
199	2532	987	229	2916	858			
200	2545	1050	230	2928	849			
201	2558	1030	231	2941	804			
202	2571	970	232	2954	817			
203	2584	1062	233	2966	810			
204	2597	1002	234	2979	809			
205	2610	965	235	2992	836			
206	2623	1006	236	3004	823			
207	2636	1020	237	3017	834			
208	2649	929	238	3030	754			
209	2661	999	239	3042	754			
210	2674	972	240	3055	799			

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APPENDIX E: MONITORING DATA: BUS STOP IN FRONT OF BUILDING 720



Figure 18: View of bus stop in front of building 720.



Figure 19: Close-up view of monitoring equipment.

E: Monitoring Data 31 May 2018; Bus Stop In Front Of Building 720

NEUTRON DATA:

Application Version : Mobile Microspec V.6.8.2
 File Name : C:\BTIData\May-31-2018\May-31-2018-Run-5\MAY-31-2018-RUN-5A-TOTAL.TXT
 Run Number : 4
 Time Run Started : May-31-2018 16:29:29
 Time Data Exported : May-31-2018 17:18:04
 Detector Channel : A
 Probe Type : N 2x2
 Duration (hh:mm:ss) : 00:37:09
 Calibration Gain (keV/ch) : [Hi-Gain] 4.97 ; [Lo-Gain] 51.20 ; [3He] 10.19
 Calibration Offset (ch) : [Hi-Gain] 0.00 ; [Lo-Gain] 0.00 ; [3He] 0.00
 Count Rate (/s) : [NE213] 0.7 ; [3He] 0.0
 Dead Time (%) : 1.96
 Scaler Counts : [Fast N] 1480; [Gamma] 55412; [3He] 58
 Comments : None

UNFOLDED NEUTRON SPECTRUM

Emin (MeV)	Emax (MeV)	Fluence (1/cm2)	Dose (mrem)	Flux (1/cm2/s)	Dose Rate (mrem/h)
0	0.01	228.474	0	0.103	0
0.01	0.5	4441.991	0.054	1.993	0.088
0.5	1	-97.23	-0.004	-0.044	-0.007
1	1.5	15.199	0.001	0.007	0.001
1.5	2	25.232	0.001	0.011	0.002
2	3	95.399	0.004	0.043	0.007
3	4	20.698	0.001	0.009	0.002
4	5	38.821	0.002	0.017	0.003
5	6	11.081	0	0.005	0.001
6	7	1.385	0	0.001	0
7	8	-0.171	0	0	0
8	9	0.335	0	0	0
9	10	-2.689	0	-0.001	0
10	12	-2.081	0	-0.001	0
12	14	0.534	0	0	0
14	16	0	0	0	0
16	18	0	0	0	0
18	20	0	0	0	0
		4776.978	0.06	2.143	0.097

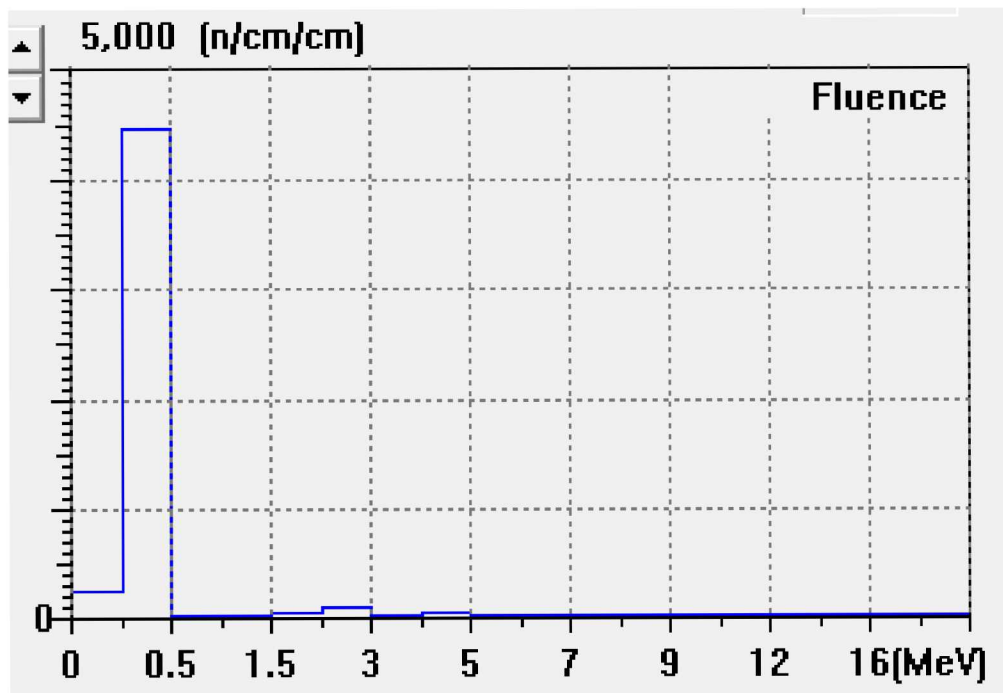


Figure 20: Measured neutron fluence at bus stop in front of IBL

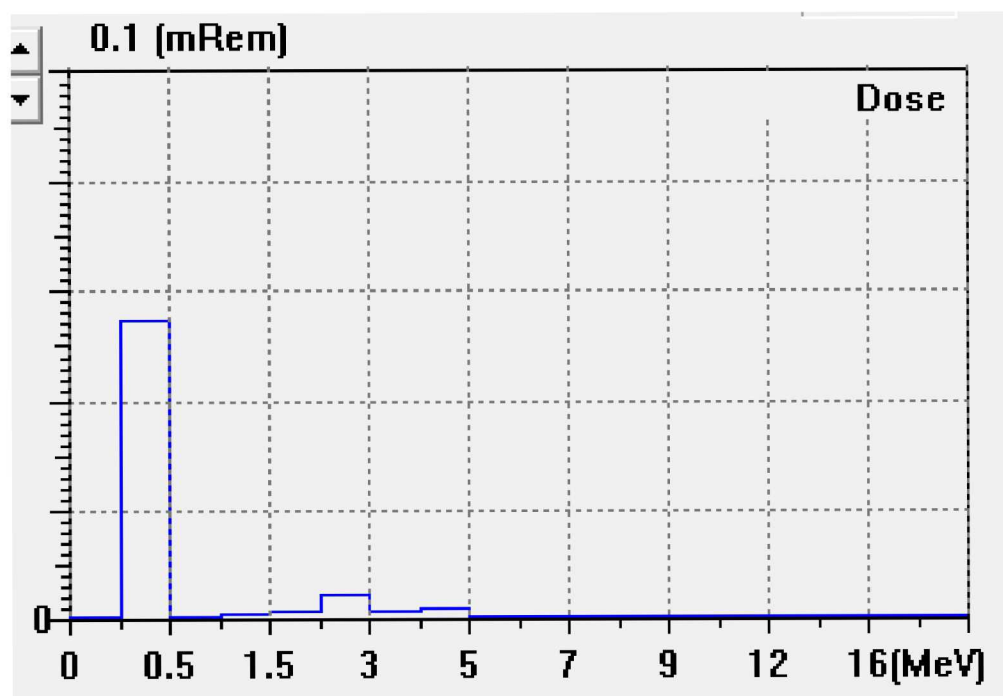


Figure 21: ICRP 74 fluence to dose conversion factors were applied to the spectrum shown in Figure 15.

E: Monitoring Data 31 May 2018; Bus Stop In Front Of Building 720

PHOTON DATA

Application Version : Mobile Microspec V.6.8.2
File Name : C:\BTIData\May-31-2018\May-31-2018-Run-5\MAY-31-2018-RUN-5B-TOTAL.TXT
Run Number : 4
Time Run Started : May-31-2018 16:29:29
Time Data Exported : May-31-2018 17:18:04
Detector Channel : B
Probe Type : G 1.5x1.5
Duration (hh:mm:ss) : 00:37:08
Calibration Gain (keV/ch) : 12.45
Calibration Offset (ch) : 2.06
Count Rate (/s) : 84.8
Dead Time (%) : 1.65
Scaler Counts : 188997
Comments : None

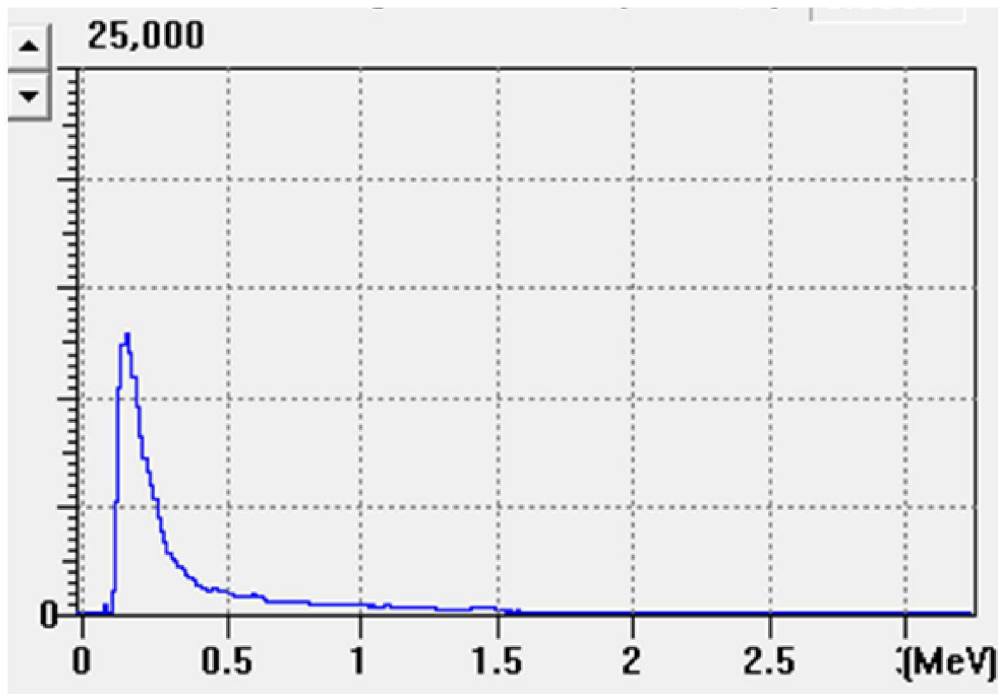


Figure 22: Measured photon spectrum at bus stop in front of building 720.

Photon Monitoring Data
IBL Bus Stop In Front Of Building 720, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
1	0	0	31	353	1822	61	736	539
2	0	0	32	365	1690	62	749	497
3	10	0	33	378	1511	63	762	509
4	21	0	34	391	1343	64	774	531
5	32	0	35	403	1255	65	787	515
6	43	0	36	416	1126	66	800	484
7	55	0	37	428	1071	67	813	464
8	67	410	38	441	1077	68	826	479
9	80	15	39	454	1149	69	839	450
10	92	1087	40	467	1076	70	852	423
11	104	5123	41	479	1060	71	865	474
12	116	10341	42	492	1043	72	878	463
13	128	12293	43	505	982	73	891	465
14	141	12771	44	518	870	74	904	486
15	153	11962	45	531	801	75	917	476
16	165	10777	46	543	810	76	930	441
17	178	9419	47	556	784	77	943	429
18	190	8084	48	569	844	78	956	442
19	202	7133	49	582	795	79	969	436
20	215	6455	50	595	886	80	982	426
21	227	5864	51	608	852	81	994	382
22	240	5255	52	620	774	82	1007	385
23	252	4421	53	633	651	83	1020	354
24	265	3752	54	646	586	84	1033	388
25	278	3273	55	659	550	85	1046	355
26	290	2743	56	672	526	86	1060	366
27	303	2521	57	684	548	87	1073	356
28	315	2399	58	697	547	88	1086	396
29	328	2181	59	710	578	89	1099	362
30	340	2041	60	723	534	90	1112	365

Photon Monitoring Data
IBL Bus Stop In Front Of Building 720, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
91	1125	325	121	1516	155	151	1908	44
92	1138	346	122	1529	123	152	1921	41
93	1151	319	123	1542	132	153	1934	31
94	1164	297	124	1556	112	154	1947	30
95	1177	313	125	1569	127	155	1960	33
96	1190	302	126	1582	119	156	1973	45
97	1204	282	127	1595	110	157	1986	23
98	1217	269	128	1608	87	158	1999	37
99	1230	263	129	1621	84	159	2012	38
100	1243	272	130	1634	106	160	2025	26
101	1256	251	131	1647	106	161	2038	18
102	1269	204	132	1660	79	162	2051	33
103	1282	222	133	1673	78	163	2064	25
104	1295	194	134	1686	65	164	2077	36
105	1308	201	135	1699	59	165	2090	31
106	1321	209	136	1713	80	166	2103	39
107	1334	196	137	1726	83	167	2116	26
108	1347	173	138	1739	60	168	2129	38
109	1360	191	139	1752	75	169	2142	24
110	1373	213	140	1765	69	170	2155	31
111	1386	219	141	1778	61	171	2168	31
112	1399	251	142	1791	69	172	2181	43
113	1412	250	143	1805	58	173	2194	34
114	1425	280	144	1818	59	174	2207	22
115	1438	328	145	1831	62	175	2220	34
116	1451	273	146	1844	49	176	2233	23
117	1464	282	147	1857	46	177	2246	26
118	1477	260	148	1870	39	178	2259	26
119	1490	206	149	1883	42	179	2272	20
120	1503	168	150	1896	42	180	2285	16

Photon Monitoring Data
IBL Bus Stop In Front Of Building 720, 31 May 2018
Location: Room 106, Visitor TLD Badge Storage Location

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
181	2298	25	211	2687	8	241	3068	4
182	2311	19	212	2700	10	242	3080	6
183	2324	20	213	2712	6	243	3093	7
184	2337	26	214	2725	6	244	3106	10
185	2350	24	215	2738	9	245	3119	9
186	2363	13	216	2750	12	246	3131	7
187	2376	12	217	2763	5	247	3144	8
188	2389	21	218	2776	12	248	3157	8
189	2402	13	219	2789	11	249	3169	4
190	2415	16	220	2801	7	250	3182	11
191	2428	16	221	2814	9	251	3195	7
192	2441	12	222	2827	5	252	3207	10
193	2454	14	223	2839	3	253	3220	4
194	2467	13	224	2852	8	254	3233	7
195	2480	16	225	2865	8			
196	2493	13	226	2877	6			
197	2506	9	227	2890	6			
198	2519	25	228	2903	4			
199	2532	26	229	2916	5			
200	2545	21	230	2928	5			
201	2558	25	231	2941	10			
202	2571	27	232	2954	7			
203	2584	28	233	2966	9			
204	2597	28	234	2979	3			
205	2610	17	235	2992	11			
206	2623	18	236	3004	8			
207	2636	17	237	3017	4			
208	2649	24	238	3030	6			
209	2661	17	239	3042	9			
210	2674	12	240	3055	6			

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**APPENDIX F: MONITORING DATA: CONNEX STORAGE AREA TO EAST OF
BLDG. 720.**



Figure 23: Monitoring location on the east side of building 720.

F: Monitoring Data 04 June 2018; Outdoors by Connex Storage Area to East of
Bldg. 720.

NEUTRON DATA:

Application Version : Mobile Microspec V.6.8.2
 File Name : C:\BTIDData\Jun-04-2018\Jun-04-2018-Run-1\JUN-04-2018-
 RUN-1A-TOTAL.TXT
 Run Number : 2
 Time Run Started : Jun-04-2018 17:05:34
 Time Data Exported : Jun-04-2018 18:38:13
 Detector Channel : A
 Probe Type : N 2x2
 Duration (hh:mm:ss) : 01:31:04
 Calibration Gain (keV/ch) : [Hi-Gain] 4.90 ; [Lo-Gain] 50.56 ; [3He] 10.19
 Calibration Offset (ch) : [Hi-Gain] 0.00 ; [Lo-Gain] 0.00 ; [3He] 0.00
 Count Rate (/s) : [NE213] 0.2 ; [3He] 0.0
 Dead Time (%) : 1.70
 Scaler Counts : [Fast N] 1250; [Gamma] 104925; [3He] 42
 Comments : None

UNFOLDED NEUTRON SPECTRUM

Emin (MeV)	Emax (MeV)	Fluence (1/cm2)	Dose (mrem)	Flux (1/cm2/s)	Dose Rate (mrem/h)
0.00	0.01	97.658	0.000	0.018	0.000
0.01	0.50	1772.089	0.022	0.324	0.014
0.50	1.00	-34.421	-0.001	0.000	0.000
1.00	1.50	3.905	0.000	-0.006	-0.001
1.50	2.00	25.562	0.001	0.005	0.001
2.00	3.00	60.782	0.003	0.011	0.002
3.00	4.00	29.999	0.002	0.005	0.001
4.00	5.00	47.065	0.002	0.009	0.001
5.00	6.00	-11.391	0.000	-0.002	0.000
6.00	7.00	23.074	0.001	0.004	0.001
7.00	8.00	0.375	0.000	0.000	0.000
8.00	9.00	4.950	0.000	0.001	0.000
9.00	10.00	-14.456	-0.001	-0.003	0.000
10.00	12.00	3.123	0.000	0.001	0.000
12.00	14.00	0.351	0.000	0.000	0.000
14.00	16.00	-9.134	0.000	-0.002	0.000
16.00	18.00	0.000	0.000	0.000	0.000
18.00	20.00	0.000	0.000	0.000	0.000
Total:		1999.532	0.028	0.366	0.018

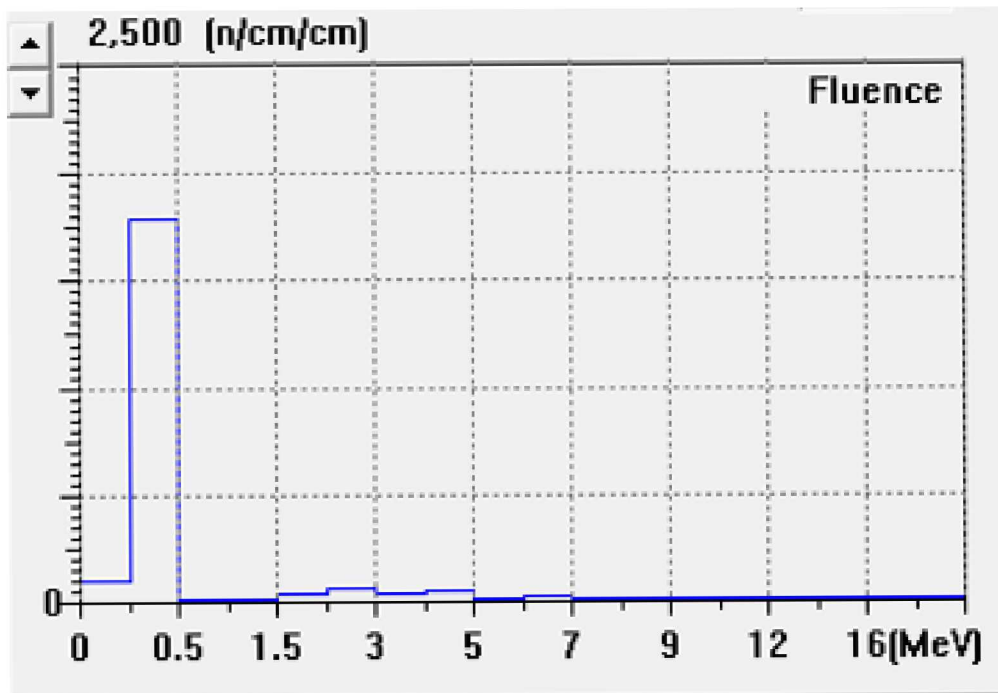


Figure 24: Measured neutron spectrum by Connex container on the east side of building 720.

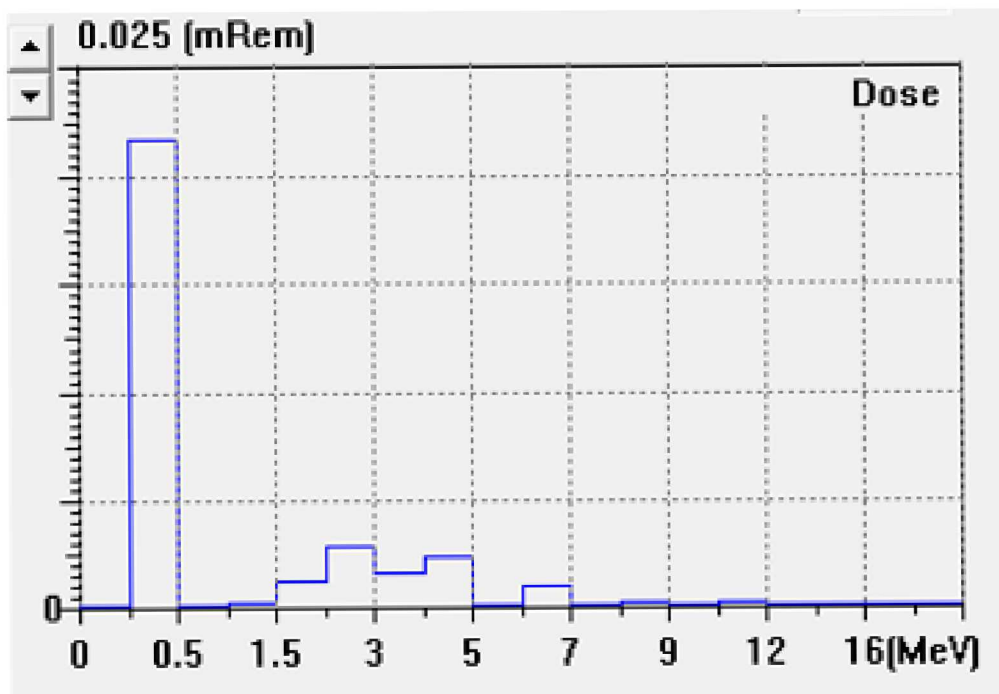


Figure 25: ICRP74 fluence to dose equivalent factors applied to the spectrum shown in Figure 18.

F: Monitoring Data 04 June 2018; Outdoors by Connex Storage Area to East of
Bldg. 720.

PHOTON DATA

Application Version : Mobile Microspec V.6.8.2
File Name : C:\BTIData\Jun-04-2018\Jun-04-2018-Run-1\JUN-04-2018-
RUN-1B-TOTAL.TXT
Run Number : 2
Time Run Started : Jun-04-2018 17:05:34
Time Data Exported : Jun-04-2018 18:38:13
Detector Channel : B
Probe Type : G 1.5x1.5
Duration (hh:mm:ss) : 01:31:04
Calibration Gain (keV/ch) : 12.44
Calibration Offset (ch) : 2.10
Count Rate (/s) : 55.9
Dead Time (%) : 1.44
Scaler Counts : 305188
Comments : None

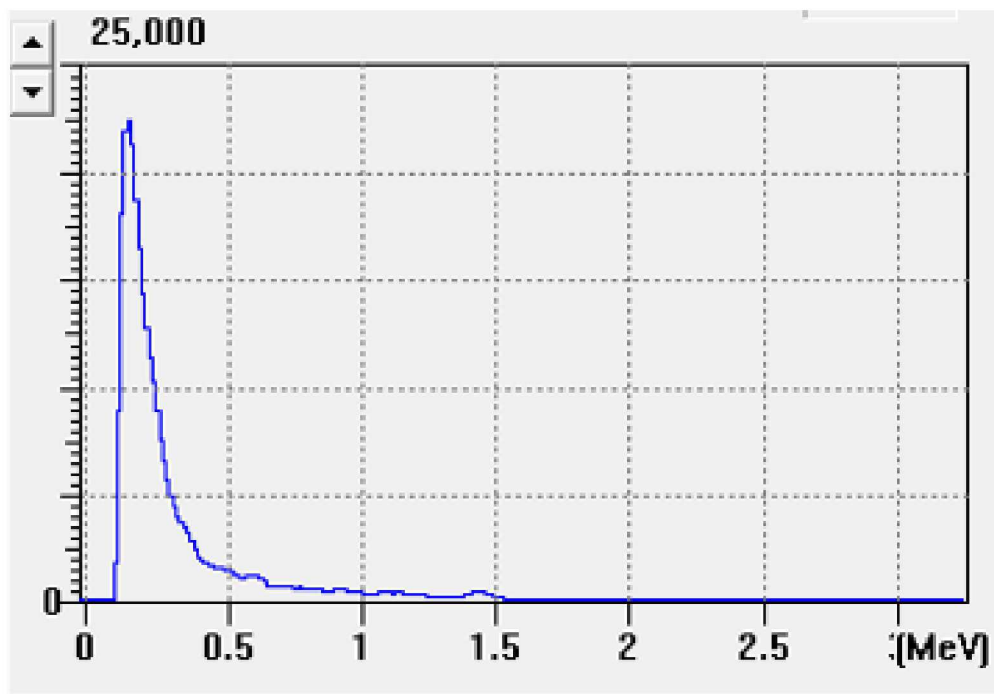


Figure 26: Photon spectrum taken by the Connex container on the east side of building 720. The dose rate of 0.0052 mrem/h is typical of normal background levels.

Photon Monitoring Data
IBL, June 4, 2018
Location: By Connex Container

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
1	0	0	31	352	3106	61	734	620
2	0	0	32	364	2782	62	747	617
3	10	0	33	377	2394	63	760	659
4	20	0	34	390	2101	64	773	569
5	31	0	35	402	1910	65	786	570
6	42	0	36	415	1788	66	799	560
7	54	0	37	427	1716	67	812	534
8	67	36	38	440	1680	68	825	498
9	79	21	39	453	1594	69	837	511
10	92	1819	40	466	1588	70	850	459
11	104	8862	41	478	1539	71	863	479
12	116	18064	42	491	1461	72	876	479
13	128	21856	43	504	1401	73	889	530
14	140	22334	44	517	1342	74	902	513
15	152	21280	45	529	1210	75	915	530
16	164	18661	46	542	1101	76	928	522
17	177	16362	47	555	1099	77	941	480
18	189	14315	48	568	1224	78	954	482
19	202	12686	49	581	1182	79	967	466
20	214	11347	50	594	1220	80	980	430
21	227	10263	51	606	1151	81	993	394
22	239	8794	52	619	1037	82	1006	337
23	252	7531	53	632	881	83	1019	363
24	264	6547	54	645	737	84	1032	358
25	277	5585	55	657	723	85	1045	341
26	289	4879	56	670	709	86	1058	403
27	302	4429	57	683	647	87	1071	387
28	314	3944	58	696	672	88	1084	389
29	327	3670	59	709	633	89	1097	409
30	339	3399	60	722	662	90	1110	357

Photon Monitoring Data
IBL, June 4, 2018
Location: By Connex Container

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
91	1123	383	121	1514	140	151	1906	51
92	1136	374	122	1527	104	152	1919	51
93	1149	360	123	1540	113	153	1932	45
94	1162	347	124	1553	99	154	1945	40
95	1175	327	125	1566	100	155	1958	47
96	1188	300	126	1579	95	156	1970	43
97	1202	266	127	1592	86	157	1983	45
98	1215	289	128	1605	82	158	1996	47
99	1228	265	129	1619	86	159	2009	45
100	1241	223	130	1632	76	160	2022	43
101	1254	198	131	1645	89	161	2035	45
102	1267	188	132	1658	83	162	2048	48
103	1280	196	133	1671	78	163	2061	52
104	1293	189	134	1684	92	164	2074	45
105	1306	172	135	1697	103	165	2087	54
106	1319	188	136	1710	78	166	2100	55
107	1332	147	137	1723	84	167	2113	55
108	1345	160	138	1736	77	168	2126	46
109	1358	200	139	1749	99	169	2139	64
110	1371	237	140	1763	89	170	2152	52
111	1384	291	141	1776	78	171	2165	47
112	1397	307	142	1789	73	172	2178	56
113	1410	390	143	1802	59	173	2191	34
114	1423	434	144	1815	71	174	2204	39
115	1436	474	145	1828	50	175	2217	58
116	1449	408	146	1841	62	176	2230	52
117	1462	345	147	1854	59	177	2243	45
118	1475	277	148	1867	54	178	2256	43
119	1488	211	149	1880	60	179	2269	38
120	1501	167	150	1893	52	180	2282	44

Photon Monitoring Data
IBL, June 4, 2018
Location: By Connex Container

Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts	Channel	Energy (keV)	Counts
181	2295	42	211	2683	9	241	3064	9
182	2308	30	212	2696	15	242	3077	7
183	2321	29	213	2709	13	243	3089	9
184	2334	40	214	2721	8	244	3102	5
185	2347	35	215	2734	7	245	3115	10
186	2360	23	216	2747	11	246	3127	14
187	2373	28	217	2760	15	247	3140	14
188	2386	32	218	2772	9	248	3153	7
189	2399	13	219	2785	15	249	3165	14
190	2412	18	220	2798	12	250	3178	9
191	2425	22	221	2810	10	251	3191	4
192	2438	19	222	2823	10	252	3203	14
193	2451	14	223	2836	7	253	3216	10
194	2464	28	224	2848	10	254	3228	13
195	2477	21	225	2861	6			
196	2490	23	226	2874	5			
197	2503	27	227	2886	11			
198	2516	39	228	2899	9			
199	2529	41	229	2912	11			
200	2542	43	230	2925	14			
201	2555	54	231	2937	14			
202	2568	41	232	2950	10			
203	2581	38	233	2963	8			
204	2594	39	234	2975	10			
205	2607	40	235	2988	8			
206	2620	33	236	3001	12			
207	2633	31	237	3013	9			
208	2645	17	238	3026	6			
209	2658	18	239	3039	7			
210	2671	10	240	3051	11			

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APPENDIX G: AVERAGE ENERGY OF MEASURED NEUTRON SPECTRA

The standard issue dosimeter at Sandia National Laboratories (SNL) is a Thermoluminescent Dosimeter (TLD). This type of dosimeter can determine whole body dose from beta, gamma and neutron radiation. However, use of this dosimeter does require information about the energy of the neutron radiation. One way to characterize the energy of neutron radiation is by means of its ‘average energy’, E_{avg} .

The average energy is calculated from a measured neutron spectrum as follows:

$$E_{avg} = \frac{\sum_{i=1}^n E_i \phi_i}{\sum_{i=1}^n \phi_i}$$

Where,

E_{avg}	is the average energy of the neutron spectrum
E_i	is the mid-range energy (MeV) of an energy bin_i
ϕ_i	is the neutron fluence in the i^{th} energy bin
n	is the total number of energy bins in the spectrum

E_{avg} is compared to the set of energy dependent dose conversion coefficients used by the Radiation Protection Dosimetry Project at SNL. This is done to select the most appropriate dose conversion factor for the badge wearer. As it is impractical to issue a specific dose conversion factor with each TLD, a “neutron code” is specified. A “neutron code” encompasses a range of dose conversion values to better average out minor variances in neutron fields within a facility. It is noted that neutron codes can be facility specific, and managers should contact their Radiation Protection Line Support Team if they have any questions.

E_{avg} was calculated for each of the measured neutron spectra presented in Appendices A through F. The results are presented in Table 3. The values presented are all very similar and clearly indicate that one neutron dose conversion factor is suitable for all locations at IBL.

The IBL source produces 14 MeV neutrons but the shielding walls are thick concrete. However, the source room ceiling is not concrete and is not designed to act as shielding. The magnitude of the calculated values for E_{avg} indicates that the neutron fields encountered at the IBL are very low energy. This is consistent with highly scattered fields created because of skyshine.

The most appropriate neutron code for the IBL, based upon the values in Table 3 is code “S”.

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APPENDIX H: NEUTRON PRODUCTION RATE

The following data was supplied by William Wampler in email to Dann Ward, dated 6/5/2018; Subject: Update on 14 MeV Neutron Test at IBL.

“DT neutron production at the IBL began at 11:00 am on Wednesday May 30 and ended at 10:00 am on Tuesday June 5. The deuterium ion beam was very stable at a current around 65 microamp, nearly double what we had during previous DT tests. The neutron production rate (determined from measured alpha yield) was $1.2 \times 10^{10}/\text{sec}$ initially but dropped to about 10% of that by the end of the run. The time integrated number of neutrons produced was 2.18×10^{15} giving a fluence at the test location of 3.0×10^{12} neutrons/cm², which are record values.”

IBL Neutron Source Output vs Time 30 May – 4 June 2018

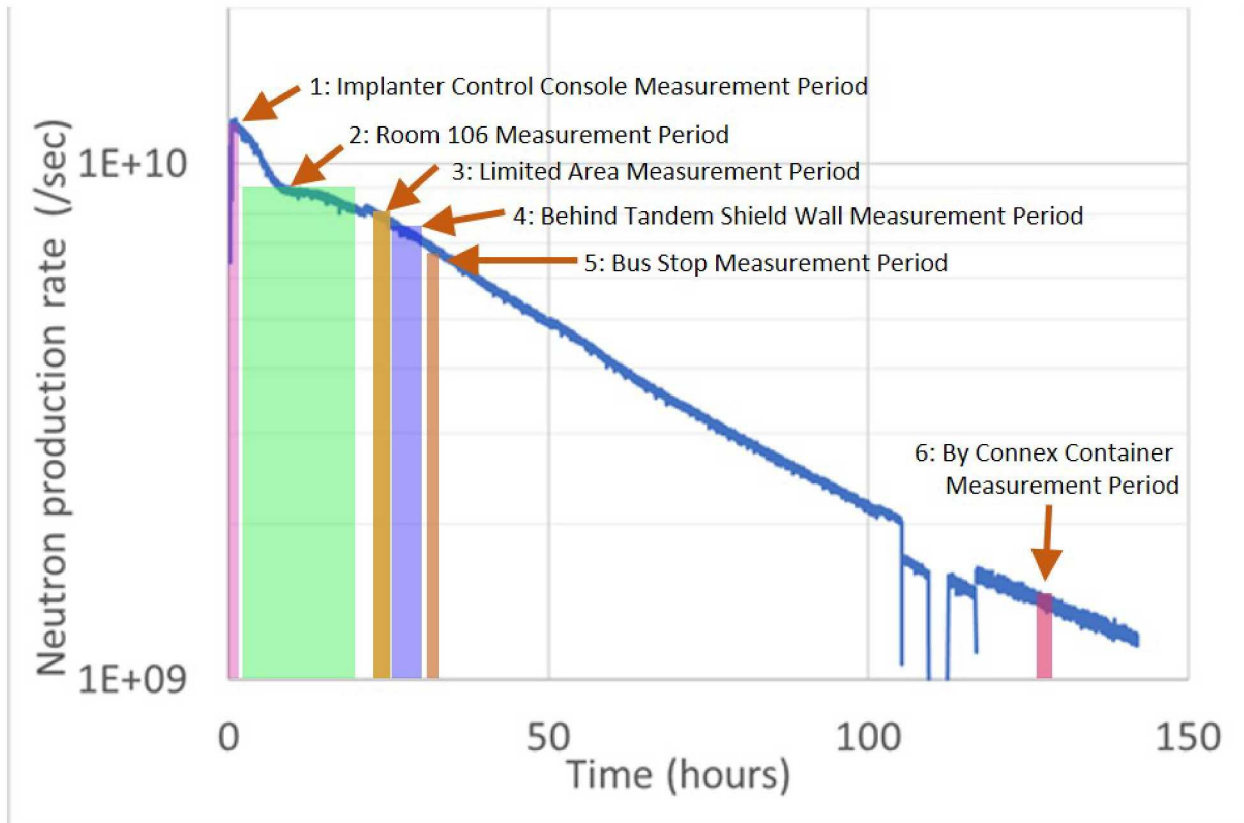


Figure 27: Neutron Source Production Rate vs Time. The left edge of each colored bar represents the start time, the right edge represents the measurement end time and the width of each bar represents the measurement duration.

The data in Figure 26 was used to calculate the neutron dose rate per 10^9 source n/s. Results are shown in section 4, Table 2.

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