Radiation Biology, Protection and Applications

(PHYS-450)

EXERCISES

Week 11

Problem 1: (Shielding of β-particles)

One curie of ^{32}P ($E_{\beta,max}$ = 1.71 MeV, E_{β} = 0.695 MeV) is dissolved in 50mL of water for an experiment. The solution is to be kept in a polyethylene bottle (ϱ = 0.93 $g.cm^{-3}$).

a) How thick should the wall of the bottle be to stop all β-particles emitted by ^{32}P?

b) What should be the thickness of lead required to ensure that the dose equivalent rate due to bremsstrahlung photons is less than 1 mrem/h at 1m?

Problem 2: (Shielding of photon sources)

Determine the thickness of an iron shield able to reduce an exposure rate of 800 mR/h from 1 MeV photons to:

a) 200 mR/h

b) 150 mR/h

N.B. : Roentgen [R] is the old unit of radiation exposure and 1R = $2.58 \cdot 10^{-4}$ $C.kg^{-1}$ of air.

Problem 3: (Shielding of photon sources, buildup factor)

A fluence of $10^5 \gamma/cm^2$ of 1.5 MeV photons strikes a two cm thick piece of lead. What is the best estimate of the total energy that reaches a receptor beyond the lead shield?

Problem 4: (Shielding of photon sources, buildup factor)

Determine the thickness of an iron shield needed to reduce the exposure rate from a point source emitting $10^8 \gamma/s$ of 1 MeV to 1 mR/h at a distance of 60 cm.
Use that the exposure rate in air for unscattered photons of energy E [MeV] is given by Exposure [mR/h] = $0.0658 \cdot \phi \cdot E \cdot (\mu_{en}/\varrho)_{air}$, where ϕ = flux of photons [$cm^{-2}.s^{-1}$] and $(\mu_{en}/\varrho)_{air}$ is the energy absorption coefficient for photons [$cm^2.g^{-1}$] of energy E [MeV].

Problem 5: (Shielding of neutron sources, buildup factor)

Estimate the dose equivalent rate 1m from an ^{239}Pu-Be source that emits $3 \cdot 10^7$ neutrons/s with an average energy of 4.5 MeV.

a) unshielded

b) shielded by 25 cm of water

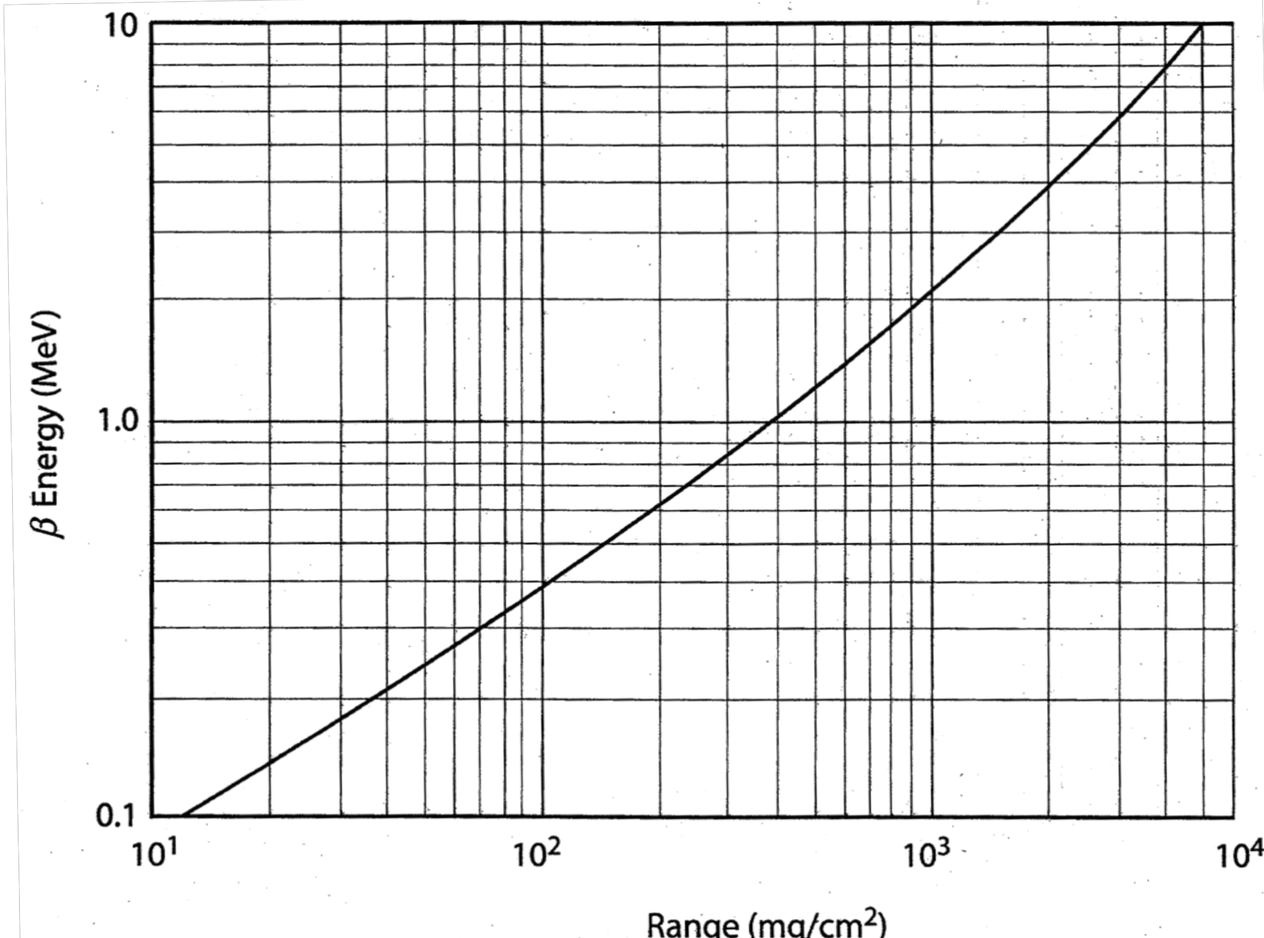

Fig. 7-9 Equivalent range of electrons in mg/cm² of low-*Z* absorbers.

Table 8-1. Percent radiation yield of electrons of initial energy *E* on different absorbers.

	Absorber (*Z*)					
E (MeV)	Water	Air	Al (13)	Cu (29)	Sn (50)	Pb (82)
0.100	0.058	0.066	0.135	0.355	0.658	1.162
0.200	0.098	0.111	0.223	0.595	1.147	2.118
0.300	0.133	0.150	0.298	0.795	1.548	2.917
0.400	0.166	0.187	0.368	0.974	1.900	3.614
0.500	0.198	0.223	0.435	1.143	2.224	4.241
0.600	0.229	0.258	0.501	1.307	2.530	4.820
0.700	0.261	0.293	0.566	1.467	2.825	5.363
0.800	0.293	0.328	0.632	1.625	3.111	5.877
0.900	0.325	0.364	0.698	1.782	3.391	6.369
1.000	0.358	0.400	0.764	1.938	3.666	6.842
1.250	0.442	0.491	0.931	2.328	4.340	7.960
1.500	0.528	0.584	1.101	2.720	4.998	9.009
1.750	0.617	0.678	1.274	3.113	5.646	10.010
2.000	0.709	0.775	1.449	3.509	6.284	10.960
2.500	0.897	0.972	1.808	4.302	7.534	12.770
3.000	1.092	1.173	2.173	5.095	8.750	14.470

Table 8-3. Half-value layers (in cm) versus photon energy for various materials[a].

Energy (MeV)	Lead (11.35 g/cm³)	Iron (7.874 g/cm³)	Aluminum (2.699 g/cm³)	Water (1.00 g/cm³)	Air (0.001205 g/cm³)	Stone concrete (2.30 g/cm³)
0.1	0.011	0.237	1.507	4.060	3.726×10^3	1.734
0.3	0.151	0.801	2.464	5.843	5.372×10^3	2.747
0.5	0.378	1.046	3.041	7.152	6.600×10^3	3.380
0.662	0.558	1.191	3.424	8.039	7.420×10^3	3.806
1.0	0.860	1.468	4.177	9.802	9.047×10^3	4.639
1.173	0.987	1.601	4.541	10.662	9.830×10^3	5.044
1.332	1.088	1.702	4.829	11.342	1.047×10^4	5.368
1.5	1.169	1.802	5.130	12.052	1.111×10^4	5.698
2.0	1.326	2.064	5.938	14.028	1.293×10^4	6.612
2.5	1.381	2.271	6.644	15.822	1.459×10^4	7.380
3.0	1.442	2.431	7.249	17.456	1.604×10^4	8.141
3.5	1.447	2.567	7.813	19.038	1.747×10^4	8.828
4.0	1.455	2.657	8.270	20.382	1.868×10^4	9.366
5.0	1.429	2.798	9.059	22.871	2.094×10^4	10.361
7.0	1.348	2.924	10.146	26.860	2.449×10^4	11.846
10.0	1.228	2.940	11.070	31.216	2.817×10^4	13.227

a Calculated from attenuation coefficients listed in Table 8-2.
Source: Data from Hubbell and Seltzer (1995).

Table 8-2. Photon attenuation (μ), mass attenuation (μ/ρ), and mass energy absorption (μ_{en}/ρ) coefficients for selected elements and compounds/mixtures (J. H. Hubbell and S. M. Seltzer).

	Dry air (sea level) (ρ = 0.001205 g/cm³)			Water, liquid (ρ = 1.00 g/cm³)			Aluminum (ρ = 2.699 g/cm³)			Iron (ρ = 7.874 g/cm³)		
Energy (keV)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)
10	0.0062	5.120	4.742	5.329	5.329	4.944	70.795	26.23	25.43	1343.304	170.6	136.90
15	0.0019	1.614	1.334	1.673	1.673	1.374	21.4705	7.955	7.487	449.4479	57.08	48.96
20	0.0009	0.7779	0.5389	0.8096	0.8096	0.5503	9.2873	3.441	3.094	202.2043	25.68	22.60
30	4.26×10^{-4}	0.3538	0.1537	0.3756	0.3756	0.1557	3.0445	1.128	0.8778	64.3778	8.176	7.251
40	2.99×10^{-4}	0.2485	0.0683	0.2683	0.2683	0.0695	1.5344	0.5685	0.3601	28.5747	3.629	3.155
50	2.51×10^{-4}	0.2080	0.0410	0.2269	0.2269	0.0422	0.9935	0.3681	0.1840	15.4173	1.958	1.638
60	2.26×10^{-4}	0.1875	0.0304	0.2059	0.2059	0.0319	0.7498	0.2778	0.1099	9.4882	1.2050	0.9555
70[a]	2.10×10^{-4}	0.1744	0.0255	0.1948	0.1948	0.0289	0.6130	0.2271	0.0713	6.2318	0.7914	0.5836
80	2.00×10^{-4}	0.1662	0.0241	0.1924	0.1924	0.0272	0.5447	0.2018	0.0551	4.6866	0.5952	0.4104
100	1.86×10^{-4}	0.1541	0.0233	0.1707	0.1707	0.0255	0.4599	0.1704	0.0379	2.9268	0.3717	0.2177
150	1.63×10^{-4}	0.1356	0.0250	0.1505	0.1505	0.0276	0.3719	0.1378	0.0283	1.5465	0.1964	0.0796
200	1.49×10^{-4}	0.1233	0.0267	0.1370	0.1370	0.0297	0.3301	0.1223	0.0275	1.1496	0.1460	0.0483
300	1.29×10^{-4}	0.1067	0.0287	0.1186	0.1186	0.0319	0.2812	0.1042	0.0282	0.8654	0.1099	0.0336
400	1.15×10^{-4}	0.0955	0.0295	0.1061	0.1061	0.0328	0.2504	0.0928	0.0286	0.7402	0.0940	0.0304
500	1.05×10^{-4}	0.0871	0.0297	0.0969	0.0969	0.0330	0.2279	0.0845	0.0287	0.6625	0.0841	0.0291
600	9.71×10^{-5}	0.0806	0.0295	0.0896	0.0896	0.0328	0.2106	0.0780	0.0285	0.6066	0.0770	0.0284

	Dry air (sea level) (ρ = 0.001205 g/cm³)			Water, liquid (ρ = 1.00 g/cm³)			Aluminum (ρ = 2.699 g/cm³)			Iron (ρ = 7.874 g/cm³)		
Energy (keV)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)	μ (cm⁻¹)	μ/ρ (cm²/g)	μ_{en}/ρ (cm²/g)
662[a]	9.34×10^{-5}	0.0775	0.0293	0.0862	0.0862	0.0326	0.2024	0.0750	0.0283	0.5821	0.0739	0.0280
800	8.52×10^{-5}	0.0707	0.0288	0.0787	0.0787	0.0321	0.1846	0.0684	0.0278	0.5275	0.0670	0.0271
1000	7.66×10^{-5}	0.0636	0.0279	0.0707	0.0707	0.0310	0.1659	0.0615	0.0269	0.4720	0.0600	0.0260
1173[a]	7.05×10^{-5}	0.0585	0.0271	0.0650	0.0650	0.0301	0.1526	0.0565	0.0261	0.4329	0.0550	0.0251
1250	6.86×10^{-5}	0.0569	0.0267	0.0632	0.0632	0.0297	0.1483	0.0550	0.0257	0.4213	0.0535	0.0247
1333[a]	6.62×10^{-5}	0.0550	0.0263	0.0611	0.0611	0.0292	0.1435	0.0532	0.0253	0.4071	0.0517	0.0243
1500	6.24×10^{-5}	0.0518	0.0255	0.0575	0.0575	0.0283	0.1351	0.0501	0.0245	0.3845	0.0488	0.0236
2000	5.36×10^{-5}	0.0445	0.0235	0.0494	0.0494	0.0261	0.1167	0.0432	0.0227	0.3358	0.0427	0.0220
3000	4.32×10^{-5}	0.0358	0.0206	0.0397	0.0397	0.0228	0.0956	0.0354	0.0202	0.2851	0.0362	0.0204
4000	3.71×10^{-5}	0.0308	0.0187	0.0340	0.0340	0.0207	0.0838	0.0311	0.0188	0.2608	0.0331	0.0199
5000	3.31×10^{-5}	0.0275	0.0174	0.0303	0.0303	0.0192	0.0765	0.0284	0.0180	0.2477	0.0315	0.0198
6000	3.04×10^{-5}	0.0252	0.0165	0.0277	0.0277	0.0181	0.0717	0.0266	0.0174	0.2407	0.0306	0.0200
6129[a]	3.01×10^{-5}	0.0250	0.0164	0.0274	0.0274	0.0180	0.0713	0.0264	0.0173	0.2403	0.0305	0.0200
7000[a]	2.83×10^{-5}	0.0235	0.0159	0.0258	0.0258	0.01723	0.0683	0.0253	0.0170	0.2370	0.0301	0.0202
7115[a]	2.82×10^{-5}	0.0234	0.0158	0.0256	0.0256	0.0172	0.0680	0.0252	0.0170	0.2368	0.0301	0.0203
10,000	2.46×10^{-5}	0.0205	0.0145	0.0222	0.0222	0.0157	0.0626	0.0232	0.0165	0.2357	0.0299	0.0211

a Coefficients for these energies were interpolated using polynomial regression.

Table 8-2. Continued.

	Copper (ρ = 8.96 g/cm^3)			Lead (ρ = 11.35 g/cm^3)			Polyethylene (ρ = 0.93 g/cm^3)			Concrete, ordinary (ρ = 2.3 g/cm^3)		
Energy (keV)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)	μ (cm^{-1})	μ/ρ (cm^2/g)	μ_{en}/ρ (cm^2/g)
10	1934.464	215.9	148.4	1482.31	130.6	124.7	1.9418	2.088	1.781	47.04	20.45	19.37
15	663.4880	74.05	57.88	1266.66	111.6	91.0	0.6930	0.7452	0.4834	14.61	6.351	5.855
20	302.7584	33.79	27.88	980.1860	86.36	68.99	0.4013	0.4315	0.1936	6.454	2.806	2.462
30	97.8432	10.92	9.349	344.1320	30.32	25.36	0.2517	0.2706	0.0593	2.208	0.9601	0.7157
40	43.5635	4.862	4.163	162.9860	14.36	12.11	0.2116	0.2275	0.0320	1.163	0.5058	0.2995
50	23.4125	2.613	2.192	91.2654	8.041	6.740	0.1938	0.2084	0.0244	0.7848	0.3412	0.1563
60	14.2733	1.5930	1.2900	56.9884	5.0210	4.1490	0.1832	0.1970	0.0224	0.6118	0.2660	0.0955
70[a]	9.2401	1.0313	0.7933	35.0670	3.0896	2.6186	0.1754	0.1886	0.0221	0.5131	0.2231	0.0638
80	6.8365	0.7630	0.5581	27.4557	2.4190	1.9160	0.1695	0.1823	0.0227	0.4632	0.2014	0.0505
100	4.1073	0.4584	0.2949	62.9812	5.5490	1.9760	0.1599	0.1719	0.0242	0.3997	0.1738	0.0365
150	1.9864	0.2217	0.1027	22.8589	2.0140	1.0560	0.1427	0.1534	0.0279	0.3303	0.1436	0.0290
200	1.3969	0.1559	0.0578	11.3330	0.9985	0.5870	0.1304	0.1402	0.0303	0.2949	0.1282	0.0287
300	1.0026	0.1119	0.0362	4.5752	0.4031	0.2455	0.1132	0.1217	0.0328	0.2523	0.1097	0.0297
400	0.8434	0.0941	0.0312	2.6366	0.2323	0.1370	0.1013	0.1089	0.0337	0.2250	0.0978	0.0302
500	0.7492	0.0836	0.0293	1.8319	0.1614	0.0913	0.0925	0.0995	0.0339	0.2050	0.0892	0.0303
600	0.6832	0.0763	0.0283	1.4165	0.1248	0.0682	0.0855	0.0920	0.0338	0.1894	0.0824	0.0302
662[a]	0.6555	0.0732	0.0279	1.2419	0.1094	0.0587	0.0823	0.0885	0.0335	0.1822	0.0792	0.0299
800	0.5918	0.0661	0.0268	1.0067	0.0887	0.0464	0.0751	0.0808	0.0330	0.1662	0.0723	0.0294
1000	0.5287	0.0590	0.0256	0.8061	0.0710	0.0365	0.0675	0.0726	0.0319	0.1494	0.0650	0.0284
1173[a]	0.4840	0.0540	0.0246	0.7020	0.0619	0.0315	0.0621	0.0668	0.0310	0.1374	0.0598	0.0276
1250	0.4714	0.0526	0.0243	0.6669	0.0588	0.0299	0.0604	0.0650	0.0305	0.1336	0.0581	0.0272
1333[a]	0.4553	0.0508	0.0239	0.6369	0.0561	0.0285	0.0584	0.0628	0.0300	0.1291	0.0561	0.0268
1500	0.4303	0.0480	0.0232	0.5927	0.0522	0.0264	0.0550	0.0591	0.0291	0.1216	0.0529	0.0260
2000	0.3768	0.0421	0.0216	0.5228	0.0461	0.0236	0.0471	0.0506	0.0268	0.1048	0.0456	0.0240
3000	0.3225	0.0360	0.0202	0.4806	0.0423	0.0232	0.0376	0.0405	0.0233	0.0851	0.0370	0.0212
4000	0.2973	0.0332	0.0199	0.4764	0.0420	0.0245	0.0320	0.0344	0.0209	0.0740	0.0322	0.0195
5000	0.2847	0.0318	0.0200	0.4849	0.0427	0.0260	0.0283	0.0305	0.0192	0.0669	0.0291	0.0184
6000	0.2785	0.0311	0.0203	0.4984	0.0439	0.0274	0.0257	0.0276	0.0179	0.0620	0.0270	0.0176
6129[a]	0.2781	0.0310	0.0203	0.5002	0.0441	0.0276	0.0254	0.0273	0.0178	0.0616	0.0268	0.0175
7000[a]	0.2757	0.0308	0.0206	0.5141	0.0453	0.0287	0.0236	0.0254	0.0169	0.0585	0.0254	0.0171
7115[a]	0.2755	0.0307	0.0207	0.5161	0.0455	0.0289	0.0235	0.0252	0.0168	0.0582	0.0253	0.0170
10,000	0.2780	0.0310	0.0217	0.5643	0.0497	0.0318	0.0199	0.0215	0.0151	0.0524	0.0228	0.0162

a Coefficients for these energies were interpolated using polynomial regression.

Table 8-4. Exposure buildup factors for photons of energy *E* versus μx (for various absorbers).

μx	Energy (MeV) 0.1	0.5	1	2	3	4	5	6	8	10
Al										
0.5	1.91	1.57	1.45	1.37	1.33	1.32	1.28	1.26	1.22	1.19
1.0	2.86	2.28	1.99	1.78	1.68	1.62	1.54	1.49	1.41	1.35
2.0	4.87	4.07	3.26	2.66	2.38	2.19	2.04	1.94	1.76	1.64
3.0	7.07	6.35	4.76	3.62	3.11	2.78	2.54	2.37	2.11	1.93
4.0	9.47	9.14	6.48	4.64	3.86	3.38	3.04	2.81	2.46	2.22
5.0	12.1	12.4	8.41	5.72	4.64	3.99	3.55	3.26	2.82	2.52
6.0	14.9	16.3	10.5	6.86	5.44	4.61	4.08	3.72	3.18	2.83
7.0	18.0	20.7	12.9	8.05	6.26	5.24	4.61	4.19	3.55	3.14
8.0	21.3	25.7	15.4	9.28	7.1	5.88	5.14	4.66	3.92	3.46
10.0	28.7	37.6	21.0	11.9	8.83	7.18	6.23	5.61	4.68	4.12
15.0	51.7	78.6	37.7	18.9	13.4	10.5	9.03	8.09	6.64	5.87
20.0	81.1	137	57.9	26.6	18.1	14.0	11.9	10.7	8.68	7.74
25.0	117	213	81.3	34.9	23.0	17.5	14.9	13.3	10.8	9.74
30.0	159	307	107	43.6	28.1	21.0	18.0	16.0	13.0	11.8
Fe										
0.5	1.26	1.48	1.41	1.35	1.32	1.3	1.27	1.25	1.22	1.19
1.0	1.4	1.99	1.85	1.71	1.64	1.57	1.51	1.47	1.39	1.33
2.0	1.61	3.12	2.85	2.49	2.28	2.12	1.97	1.87	1.71	1.59
3.0	1.78	4.44	4	3.34	2.96	2.68	2.46	2.3	2.04	1.86
4.0	1.94	5.96	5.3	4.25	3.68	3.29	2.98	2.76	2.41	2.16
5.0	2.07	7.68	6.74	5.22	4.45	3.93	3.53	3.25	2.81	2.5
6.0	2.2	9.58	8.31	6.25	5.25	4.6	4.11	3.78	3.24	2.87
7.0	2.31	11.7	10.0	7.33	6.09	5.31	4.73	4.33	3.71	3.27
8.0	2.41	14.0	11.8	8.45	6.96	6.05	5.38	4.92	4.2	3.71
10.0	2.61	19.1	15.8	10.8	8.8	7.6	6.75	6.18	5.3	4.69
15.0	3.01	35.1	27.5	17.4	13.8	11.9	10.7	9.85	8.64	7.88

Table 8-4. Continued.

μx	Energy (MeV) 0.1	0.5	1	2	3	4	5	6	8	10
20.0	3.33	55.4	41.3	24.6	19.4	16.8	15.2	14.2	12.9	12.3
25.0	3.61	79.9	57.0	32.5	25.4	22.1	20.3	19.3	18.2	18.1
30.0	3.86	108	74.5	40.9	31.7	27.9	25.9	25.1	24.5	25.7
Sn										
0.5	1.35	1.32	1.33	1.27	1.29	1.28	1.31	1.31	1.33	1.31
1.0	1.38	1.61	1.69	1.57	1.56	1.51	1.55	1.54	1.6	1.57
2.0	1.41	2.15	2.4	2.17	2.07	1.96	1.97	1.94	2.04	2.05
3.0	1.43	2.68	3.14	2.82	2.64	2.45	2.43	2.38	2.51	2.61
4.0	1.45	3.16	3.86	3.51	3.25	3.0	2.54	2.87	3.05	3.27
5.0	1.47	3.63	4.6	4.23	3.92	3.6	3.52	3.43	3.69	4.09
6.0	1.49	4.14	5.43	5.03	4.68	4.29	4.19	4.09	4.45	5.07
7.0	1.5	4.64	6.27	5.87	5.48	5.04	4.93	4.83	5.34	6.26
8.0	1.52	5.13	7.11	6.74	6.32	5.84	5.74	5.65	6.36	7.69
10.0	1.54	6.13	8.88	8.61	8.19	7.65	7.63	7.63	8.94	11.5
15.0	1.58	8.74	13.8	14.0	13.8	13.5	14.1	14.9	19.7	29.6
20.0	1.61	11.4	19.1	20.1	20.5	21.1	23.5	26.4	40.7	72.1
25.0	1.64	14.0	24.5	26.9	28.1	30.6	36.2	43.9	79.7	168
30.0	1.66	16.5	30.0	34.2	36.6	42.1	53.0	69.3	150	377
Pb										
0.5	1.51	1.14	1.2	1.21	1.23	1.21	1.25	1.26	1.3	1.28
1.0	2.04	1.24	1.38	1.4	1.4	1.36	1.41	1.42	1.51	1.51
2.0	3.39	1.39	1.68	1.76	1.73	1.67	1.71	1.73	1.9	2.01
3.0	5.6	1.52	1.95	2.14	2.1	2.02	2.05	2.08	2.36	2.63
4.0	9.59	1.62	2.19	2.52	2.5	2.4	2.44	2.49	2.91	3.42
5.0	17.0	1.71	2.43	2.91	2.93	2.82	2.88	2.96	3.59	4.45
6.0	30.6	1.8	2.66	3.32	3.4	3.28	3.38	3.51	4.41	5.73
7.0	54.9	1.88	2.89	3.74	3.89	3.79	3.93	4.13	5.39	7.37
8.0	94.7	1.95	3.1	4.17	4.41	4.35	4.56	4.84	6.58	9.44

Table 8-4. Continued.

μx	Energy (MeV) 0.1	0.5	1	2	3	4	5	6	8	10
10.0	294	2.1	3.51	5.07	5.56	5.61	6.03	6.61	9.73	15.4
15.0	5800	2.39	4.45	7.44	8.91	9.73	11.4	13.7	25.1	50.8
20.0	1.33×10^5	2.64	5.27	9.98	12.9	15.4	19.9	26.6	62.0	161
25.0	3.34×10^6	2.85	5.98	12.6	17.5	23.0	32.9	49.6	148	495
30.0	8.87×10^7	3.02	6.64	15.4	22.5	32.6	52.2	88.9	344	1470
U										
0.5	1.04	1.11	1.17	1.19	1.2	1.19	1.23	1.24	1.28	1.27
1.0	1.06	1.19	1.31	1.35	1.35	1.32	1.37	1.38	1.48	1.49
2.0	1.08	1.3	1.53	1.65	1.64	1.6	1.64	1.66	1.85	1.97
3.0	1.1	1.39	1.73	1.95	1.95	1.89	1.94	1.98	2.27	2.56
4.0	1.11	1.45	1.9	2.25	2.28	2.21	2.27	2.33	2.78	3.31
5.0	1.12	1.52	2.07	2.56	2.62	2.55	2.63	2.74	3.39	4.26
6.0	1.13	1.58	2.23	2.88	2.99	2.93	3.04	3.19	4.11	5.43
7.0	1.14	1.63	2.38	3.19	3.38	3.33	3.49	3.71	4.96	6.9
8.0	1.14	1.68	2.52	3.51	3.78	3.76	3.99	4.28	5.97	8.73
10.0	1.16	1.77	2.78	4.17	4.64	4.72	5.14	5.68	8.61	13.9
15.0	1.18	1.96	3.35	5.84	7.06	7.72	9.1	11.0	20.8	43.4
20.0	1.2	2.11	3.82	7.54	9.8	11.6	15.1	20.1	48.6	131
25.0	1.22	2.23	4.23	9.27	12.8	16.5	23.7	35.4	110	385
30.0	1.23	2.33	4.59	11.0	16.0	22.5	36.0	60.4	244	1100
H_2O										
0.5	2.37	1.6	1.47	1.38	1.34	1.31	1.28	1.27	1.23	1.2
1.0	4.55	2.44	2.08	1.83	1.71	1.63	1.56	1.51	1.43	1.37
2.0	11.8	4.88	3.62	2.81	2.46	2.24	2.08	1.97	1.8	1.68
3.0	23.8	8.35	5.5	3.87	3.23	2.85	2.58	2.41	2.15	1.97
4.0	41.3	12.8	7.68	4.98	4	3.46	3.08	2.84	2.46	2.25
5.0	65.2	18.4	10.1	6.15	4.8	4.07	3.58	3.27	2.82	2.53
6.0	96.7	25.0	12.8	7.38	5.61	4.68	4.08	3.7	3.15	2.8

Table 8-4. Continued.

μx	Energy (MeV) 0.1	0.5	1	2	3	4	5	6	8	10
7.0	137	32.7	15.8	8.65	6.43	5.3	4.58	4.12	3.48	3.07
8.0	187	41.5	19.0	9.97	7.27	5.92	5.07	4.54	3.8	3.34
10.0	321	62.9	26.1	12.7	8.97	7.16	6.05	5.37	4.44	3.86
15.0	938	139	47.7	20.1	13.3	10.3	8.49	7.41	5.99	5.14
20.0	2170	252	74.0	28	17.8	13.4	10.9	9.42	7.49	6.38
25.0	4360	403	104	36.5	22.4	16.5	13.3	11.4	8.96	7.59
30.0	7970	594	139	45.2	27.1	19.7	15.7	13.3	10.4	8.78
Air										
0.5	2.35	1.6	1.47	1.38	1.34	1.31	1.29	1.27	1.23	1.2
1.0	4.46	2.44	2.08	1.83	1.71	1.63	1.57	1.52	1.43	1.37
2.0	11.4	4.84	3.6	2.81	2.46	2.25	2.09	1.97	1.8	1.68
3.0	22.5	8.21	5.46	3.86	3.22	2.85	2.6	2.41	2.15	1.97
4.0	38.4	12.6	7.6	4.96	4	3.46	3.11	2.85	2.5	2.26
5.0	59.9	17.9	10.0	6.13	4.79	4.07	3.61	3.28	2.84	2.54
6.0	87.8	24.2	12.7	7.35	5.6	4.69	4.12	3.71	3.17	2.82
7.0	123	31.6	15.6	8.61	6.43	5.31	4.62	4.14	3.51	3.1
8.0	166	40.1	18.8	9.92	7.26	5.94	5.12	4.57	3.84	3.37
10.0	282	60.6	25.8	12.6	8.97	7.19	6.13	5.42	4.49	3.92
15.0	800	134	47.0	20	13.4	10.3	8.63	7.51	6.08	5.25
20.0	1810	241	72.8	27.9	17.9	13.5	11.1	9.58	7.64	6.55
25.0	3570	385	103	36.2	22.5	16.7	13.6	11.6	9.17	7.84
30.0	6430	567	136	45	27.2	19.9	16.1	13.6	10.7	9.11
Concrete										
0.5	1.89	1.57	1.45	1.37	1.33	1.31	1.27	1.26	1.22	1.19
1.0	2.78	2.27	1.98	1.77	1.67	1.61	1.53	1.49	1.41	1.35
2.0	4.63	4.03	3.24	2.65	2.38	2.18	2.04	1.93	1.76	1.64
3.0	6.63	6.26	4.72	3.6	3.09	2.77	2.53	2.37	2.11	1.93
4.0	8.8	8.97	6.42	4.61	3.84	3.37	3.03	2.8	2.45	2.22

Table 14-4. Fluence rates for monoenergetic neutrons that correspond to a dose equivalent rate of 1 mrem/h.

Neutron energy (eV)	Fluence rate (n/cm^2 s) for 1 mrem/h	
	10 CFR 20[a]	NCRP-112[b]
0.025 (thermal)	272	112
0.1	272	112
1	224	112
10	224	112
10^2	232	116
10^3	272	112
10^4	280	120
10^5	46.0	16.0
5×10^5	10.8	6.40
10^6	7.6	3.88
5×10^6	6.4	3.88
10^7	6.8	3.20
1.4×10^7	4.8	2.72
6×10^7	4.4	–
10^8	5.6	–

a Adapted from Title 10, Code of Federal Regulations, Part 20 (1993) by the US Nuclear Regulatory Commission (the rates incorporate neutron quality factors of 2.0 for thermal and low-energy neutrons and 2.5–11 for higher energy neutrons).

b These fluence rates are based on NCRP Report 112 (1987) which recommends increasing Q for neutrons by a factor of 2.5 for thermal neutrons and 2.0 for all other energies.

Table 14-5. Neutron removal coefficients Σ_{nr} for fission neutrons in several common materials surrounded by sufficient hydrogenous material to absorb neutrons that are degraded in energy due to scattering interactions.

Medium	Σ_{nr} (cm^{-1})
Sodium	0.032
Graphite	0.078
Carbon	0.084
Concrete (6% H_2O)	0.089
D_2O	0.092
Zirconium	0.101
H_2O	0.103
Paraffin	0.106
Polyethylene	0.111
Lead	0.118
Beryllium	0.132
Iron	0.156
Copper	0.167
Uranium	0.182
Tungsten	0.212

Source: Report TID-25951, 1973.