UNIVERSITI SAINS MALAYSIA

Peperiksaan Kursus Semasa Cuti Panjang
Sidang Akademik 2003/2004

April 2004

ZCT 533/4 - Dosimetry And Radiation Protection
[Dosimetri Dan Perlindungan Sinaran]

Duration: 3 hours
[Masa : 3 jam]

Please check that the examination paper consists of **THIRTEEN** pages of printed material before you begin the examination.

*[Sila pastikan bahawa kertas peperiksaan ini mengandungi **TIGA BELAS** muka surat yang bercetak sebelum anda memulakan peperiksaan ini.]*

Instruction: Answer all **FIVE (5)** questions. Students are allowed to answer all questions in Bahasa Malaysia or in English.

*[**Arahan**: Jawab kesemua **LIMA** soalan. Pelajar dibenarkan menjawab semua soalan sama ada dalam Bahasa Malaysia atau Bahasa Inggeris.]*

1. (a) Photons of energy 1 MeV has
[(a) Foton bertenaga 1 MeV mempunyai]

$$\left(\frac{\mu_{en}}{\rho}\right)_{air} = 2.8\times10^{-3} \ \text{m}^2\ \text{kg}^{-1}$$

Determine the energy fluence and the photon fluence needed for an exposure of 100 R.
[Tentukan fluens tenaga dan fluens foton yang diperlukan untuk suatu dedahan 100 R.]

[4 marks]

(b) Explain the differences between energy transfer and the net energy transfer in a volume V.
[(b) Jelaskan perbezaan-perbezaan di antara pemindahan tenaga dengan pemindahan tenaga bersih dalam suatu isipadu V.]

[4 marks

(c) Consider a parallel beam of 1 MeV photons incident perpendicularly to an aluminium plate at a fluence rate of 10^{10} m^{-2} s^{-1}. The thickness of the aluminium is 1.2 cm and its density is 2700 kg m^{-3}.
[(c) Pertimbangkan suatu alur foton 1 MeV yang datang secara serenjang kepada suatu plat aluminium pada suatu kadar fluens 10^{10} m^{-2} s^{-1}. Ketebalan aluminium ialah 1.2 cm dan ketumpatannya ialah 2700 kg m^{-3}.]

(i) Calculate the ratio of photons transmitted through without undergoing any interaction in the aluminium.
[(i) Hitung nisbah foton yang ditransmissikan tanpa mengalami sebarang interaksi dalam aluminium.]

(ii) Calculate the ratio of the photon energy passing through the aluminium.
[(ii) Hitung nisbah tenaga foton yang melalui aluminium.]

(iii) Determine the energy deposited in the aluminium.
[(iii) Tentukan tenaga yang diendapkan dalam aluminium.]

(iv) Determine the ratio of the kinetic energy of the electrons emitted as bremsstrahlung.
[(iv) Tentukan nisbah tenaga kinetik elektron yang dipancarkan sebagai bremsstrahlung.]

[12 marks]

2. (a) Describe briefly the following:
[(a) Perihalkan perkara-perkara berikut:]

(i) Radiation equlibrium (RE)
[(i) Keseimbangan sinaran (RE)]

(ii) Charged-particle equilibrium (CPE)
[(ii) Keseimbangan zarah bercas (CPE)]

(iii) Transient charged-particle equilibrium (TCPE).
[(iii) Keseimbangan transient zarah bercas (TCPE).]

State their importance in the measurement of exposure and dose.
[Nyatakan kepentingan perkara-perkara tersebut dalam pengukuran dedahan dan dos.]

[8 marks]

(b) A 8-MeV γ-ray enters a volume V and undergoes pair-production interaction. The electron and positron produced have identical energies. The electron spends half of its kinetic energy before escaping from V. The positron spends three quarter of its energy before being annihilated. The resulting photons escape from V. Determine the kerma and the absorbed dose in V given that the volume $V = 1$ cm^3 and its density is 1 kg m^{-3}.

[(b) Suatu sinar γ 8-MeV memasuki suatu isipadu V dan mengalami interaksi penghasilan pasangan. Elektron dan positron yang terhasil mempunyai tenaga yang seiras. Elektron itu menghabiskan setengah tenaga kinetiknya sebelum keluar dari V. Positron itu pula menghabiskan tiga suku tenaganya sebelum dihapuskan. Foton-foton yang terhasil terkeluar dari V. Tentukan kerma dan tenaga terserap dalam V jika diberikan isipadu V = 1 cm^3 dan ketumpatannya ialah 1 kg m^{-3}.]

[12 marks]

3. (a) Describe the meaning of the mass stopping power and the restricted mass stopping power.
[(a) Perihalkan maksud kuasa penghenti jisim dan kuasa penghenti jisim terbatas.]

[6 marks]

(b) Describe the Bragg-Gray cavity theory and the assumptions involved.
[(b) Perihalkan teori rongga Bragg-Gray dan anggapan-anggapan yang terlibat.]

[6 marks]

(c) A TLD chip with a thickness of 0.5 mm is used to determine the absorbed dose in water due to a Co-60 gamma source. (i) Could the Bragg-Gray cavity theorem be used to determine the absorbed dose in water? Explain. (ii) Describe how the absorbed dose in the chip is determined.

[(c) Suatu cip TLD dengan ketebalan 0.5 mm digunakan untuk menentukan dos terserap dalam air akibat suatu sumber gamma Co-60. (i) Bolehkan teorem rongga Bragg-Gray cavity digunakan untuk menentukan dos terserap dalam air? Jelaskan. (ii) Perihalkan bagaimana dos terserap dalam cip itu ditentukan.]

[8 marks]

4. (a) Describe the construction of a free-air ion chamber. Explain how it is used to measure exposure at a point in air.

[(a) Perihalkan binaan kebuk ion udara bebas. Jelaskan bagaimana ia digunakan untuk mengukur dedahan pada suatu titik dalam udara.]

[10 marks]

(b) A free-air ion chamber has a diaphragm opening of 1.00 cm diameter and a collecting plate 12 cm long. The separation between the collecting plate and the guard plate is 0.5 mm. The distance between the diaphragm and the front edge of the collecting plate is 30 cm. The temperature of the dry air in the chamber is 23.1°C, its pressure is 755 torr and $(\mu/\rho)_{air} = 0.155$ cm^2 g^{-1}. Assume that no x-rays is scattered into the chamber and also all electrons are stopped after their full ranges.

[(b) Suatu kebuk ion udara bebas mempunyai suatu bukaan diafram berdiameter 1.00 cm dan suatu plat pengumpul 12 cm panjang. Pemisahan di antara plat pengumpul dan plat pengawal ialah 0.5 mm. Jarak di antara diafram dan pinggir hadapan plat pengumpul ialah 30 cm. Suhu udara kering dalam kebuk ialah 23.1°C, tekanannya ialah 755 torr dan $(\mu/\rho)_{air} = 0.155$ cm^2 g^{-1}. Anggap tiada sinar-x yang diserakkan ke dalam kebuk dan juga kesemua elektron berhenti selepas mencapai julat penuhnya.

(i) Calculate the exposure at the diaphragm for charge $Q = 6.17 \times 10^{-7}$ C (corrected for ion recombination). Give your answer in C kg^{-1} and also in R. The density of dry air at 0°C and 760 torr is 1.293 kg m^{-3}

[(i) Hitung dedahan pada diafram bagi cas $Q = 6.17 \times 10^{-7}$ C (telah dibetulkan bagi penggabungan semula ion). Berikan jawapan anda dalam C kg^{-1} dan juga dalam R. Ketumpatan udara kering pada 0°C dan 760 torr ialah 1.293 kg m^{-3}]

(ii) Calculate the absorbed dose in air at that point.
[(ii) Hitung dos terserap pada titik itu.]

[10 marks]

5. (a) Describe the type of thermal neutron reaction occuring in tissue. What is its relative contribution in term of tissue size.
[(a) Perihalkan jenis tindakbalas neutron terma yang berlaku dalam tisu. Berapakah sumbangan relatifnya dalam sebutan saiz tisu.]

[5 marks]

(b) Discuss the ALARA concept.
[(b) Bincangkan konsep ALARA.]

[5 marks]

(c) Define maximum permissible dose (MPD). Describe the differences between occupational MPD and non-occupational MPD.
[(c) Takrifkan dos maksimum yang dibenarkan (MPD). Perihalkan perbezaan-perbezaan di antara MPD pekerja dan MPD bukan pekerja.]

[10 marks]

APPENDIX A.2. Conversion Factors

1 kg	= 5.6095×10^{29} MeV
1 amu	= 931.50 MeV
Electron rest mass	= 0.51100 MeV
Proton rest mass	= 938.26 MeV
Neutron rest mass	= 939.55 MeV
1 electron volt (eV)	= 1.6022×10^{-19} J
	= 1.6022×10^{-12} erg
1 joule (J)	= 10^7 erg
1 coulomb (C)	= 2.9979×10^9 esu
1 gray (Gy)	= 1 J/kg = 10^2 rad = 10^4 erg/g
1 sievert (Sv)	= 1 J/kg

Energy-wavelength conversion:

1.23985×10^{-6} eV m

12.3985 keV Å

Exposure conversion:

1 roentgen (R) = 2.58×10^{-4} C/kg

1 C/kg = 3876 R

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Appendix B.2. Data Table for Compounds and Mixtures[a]

Material	Density (g/cm^3)[c]	Electron density (10^{23} e/g)	I (eV)[d]
A-150 plastic[b]	1.127	3.306	65.1
Adipose tissue (Fat, ICRP)[b]	0.92	3.363	63.2
Air[b]	1.205×10^{-3}	3.006	85.7
Bone, cortical (ICRP)[b]	1.85	3.139	106.4
Calcium fluoride, CaF_2	3.18	2.931	166
Carbon dioxide, CO_2	1.842×10^{-3}	3.010	85.0
Cesium iodide, CsI	4.51	2.503	553
Lithium fluoride, LiF	2.64	2.786	94.0
Lucite, $(C_5H_8O_2)_n$	1.19	3.248	74.0
Muscle, skeletal (ICRP)[b]	1.04	3.308	75.3
Mylar, $(C_{10}H_8O_4)_n$	1.40	3.134	78.7
Nylon, type 6 $(C_6H_{11}NO)_n$	1.14	3.299	63.9
Polycarbonate $(C_{16}H_{14}O_3)_n$	1.20	3.173	73.1
Polyethylene $(C_2H_4)_n$	0.94	3.435	57.4
Polyimide $(C_{22}H_{10}N_2O_5)$	1.42	3.087	79.6
Polypropylene $(C_3H_5)_n$	0.90	3.372	59.2
Polystyrene $(C_8H_8)_n$	1.06	3.238	68.7
Polyvinyl Chloride $(C_2H_3Cl)_n$	1.30	3.083	108.2
Pyrex (borosilicate glass)[b]	2.23	2.993	134
Silicon dioxide, SiO_2	2.32	3.007	139.2
Silver bromide, AgBr	6.47	2.629	487
Sodium iodide, NaI	3.67	2.571	452
Teflon, $(C_2F_4)_n$	2.20	2.890	99.1
TE gas (methane-based)[b]	1.064×10^{-3}	3.312	61.2
TE gas (propane-based)[b]	1.826×10^{-3}	3.314	59.5
TE liquid (no sucrose)[b]	1.070	3.313	74.2
Water, H_2O	0.9982	3.343	75.0

[a] Data from Berger and Seltzer (1983)

[b] See compositions in Appendix B.3

[c] Assuming $T = 20°C.$, $P = 1$ atm., and Charles' Law for gases applies.

[d] I is the mean excitation potential for stopping power, see Chapter 8.

APPENDIX D.3. (*Continued*)

Photon Energy (MeV)	Tin			Photon Energy (MeV)	Lead		
	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ		μ/ρ	μ_{tr}/ρ	μ_{en}/ρ
0.0010	11130	11110	11110	M_1 edge	—		
0.0015	3960	3950	3950	0.003854	1493	1454	1453
0.0020	1963	1954	1954				
0.0030	713	705	705	0.004	1333	1298	1297
				0.005	767	747	747
0.0039288	367	360	360	0.006	493	479	479
L_3 edge				0.008	238	230	230
0.0039288	1118	1067	1067				
				0.010	136.6	131.0	130.7
0.0040	1067	1019	1019				
				0.0130406	70.1	66.2	66.0
0.0041573	973	930	930	L_3 edge			
L_2 edge				0.0130406	165.7	128.8	128.8
0.0041573	1244	1187	1187				
				0.015	114.7	91.7	91.7
0.0044648	1016	971	971				
L_1 edge				0.0152053	112.0	89.6	89.6
0.0044648	1264	1207	1207	L_2 edge			
				0.0152053	145.4	113.0	113.0
0.005	919	880	880				
0.006	561	540	539	0.015855	129.3	101.7	101.6
0.008	259	250	249	L_1 edge			
				0.015855	159.2	123.0	123.0
0.010	141.6	136.5	136.4				
0.015	45.8	43.7	43.6	0.02	85.5	69.2	69.1
0.020	21.2	19.83	19.81	0.03	29.1	24.6	24.6
0.0291947	7.61	6.83	6.82	0.04	13.80	11.83	11.78
K edge				0.05	7.71	6.57	6.54
0.0291947	45.4	16.70	16.69	0.06	4.87	4.11	4.08
				0.08	2.37	1.924	1.908
0.030	42.1	16.18	16.17	0.088005	1.865	1.494	1.481
0.04	18.77	9.97	9.96	K edge			
0.05	10.20	6.25	6.24	0.088005	7.30	2.47	2.47
0.06	6.34	4.20	4.19				
0.08	3.07	2.19	2.18	0.10	5.78	2.28	2.28
				0.15	2.07	1.164	1.154
0.10	1.720	1.257	1.250	0.2	1.014	0.637	0.629
0.15	0.634	0.446	0.442	0.3	0.406	0.265	0.259
0.20	0.333	0.211	0.209				
0.30	0.1649	0.0853	0.0843	0.4	0.233	0.1474	0.1432
				0.5	0.1614	0.0984	0.0951
0.4	0.1163	0.0536	0.0530	0.6	0.1249	0.0737	0.0710
0.5	0.0948	0.0423	0.0416	0.8	0.0886	0.0503	0.0481
0.6	0.0811	0.0358	0.0353				
0.8	0.0667	0.0301	0.0294	1.0	0.0708	0.0396	0.0377
				1.5	0.0518	0.0288	0.0271
1.0	0.0578	0.0270	0.0264	2	0.0455	0.0259	0.0240
1.5	0.0462	0.0233	0.0226	3	0.0417	0.0260	0.0234
2.0	0.0410	0.0220	0.0210				
3.0	0.0366	0.0219	0.0205	4	0.0415	0.0281	0.0245
				5	0.0424	0.0306	0.0259
4	0.0355	0.0232	0.0212	6	0.0436	0.0331	0.0272
5	0.0353	0.0247	0.0221	8	0.0467	0.0378	0.0294
6	0.0357	0.0262	0.0230				
8	0.0370	0.0292	0.0245	10	0.0496	0.0419	0.0310
10	0.0387	0.0319	0.0258				

APPENDIX D.3. *(Continued)*

Photon Energy (MeV)	Air			Water			ICRU Compact Bone			ICRU Striated Muscle		
	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ	μ/ρ	μ_{tr}/ρ	μ_{en}/ρ
0.01	5.04	4.61	4.61	5.21	4.79	4.79	20.3	19.2	19.2	5.30	4.87	4.87
0.015	1.56	1.27	1.27	1.60	1.28	1.28	6.32	5.84	5.84	1.64	1.32	1.32
0.02	0.758	0.511	0.511	0.778	0.512	0.512	2.79	2.46	2.46	0.796	0.533	0.533
0.03	0.350	0.148	0.148	0.371	0.149	0.149	0.962	0.720	0.720	0.375	0.154	0.154
0.04	0.248	0.0668	0.0668	0.267	0.0677	0.0677	0.511	0.304	0.304	0.267	0.0701	0.0701
0.05	0.206	0.0406	0.0406	0.225	0.0418	0.0418	0.346	0.161	0.161	0.224	0.0431	0.0431
0.06	0.187	0.0305	0.0305	0.205	0.0320	0.0320	0.273	0.0998	0.0998	0.204	0.0328	0.0328
0.08	0.167	0.0243	0.0243	0.185	0.0262	0.0262	0.209	0.0537	0.0537	0.183	0.0264	0.0264
0.10	0.155	0.0234	0.0234	0.171	0.0256	0.0256	0.181	0.0387	0.0387	0.170	0.0256	0.0256
0.15	0.136	0.0250	0.0250	0.151	0.0277	0.0277	0.150	0.0305	0.0305	0.150	0.0275	0.0275
0.2	0.124	0.0268	0.0268	0.137	0.0297	0.0297	0.133	0.0301	0.0301	0.136	0.0294	0.0294
0.3	0.107	0.0287	0.0287	0.119	0.0319	0.0319	0.114	0.0310	0.0310	0.118	0.0317	0.0317
0.4	0.0954	0.0295	0.0295	0.106	0.0328	0.0328	0.102	0.0315	0.0315	0.105	0.0325	0.0325
0.5	0.0868	0.0297	0.0296	0.0966	0.0330	0.0330	0.0926	0.0317	0.0317	0.0958	0.0328	0.0328
0.6	0.0804	0.0296	0.0295	0.0894	0.0329	0.0329	0.0856	0.0315	0.0314	0.0886	0.0326	0.0325
0.8	0.0706	0.0289	0.0289	0.0785	0.0321	0.0321	0.0751	0.0307	0.0306	0.0778	0.0318	0.0318
1.0	0.0635	0.0280	0.0278	0.0706	0.0311	0.0309	0.0675	0.0297	0.0295	0.0699	0.0308	0.0306
1.5	0.0517	0.0256	0.0254	0.0575	0.0284	0.0282	0.0549	0.0272	0.0270	0.0570	0.0282	0.0280
2	0.0444	0.0236	0.0234	0.0493	0.0262	0.0260	0.0472	0.0251	0.0249	0.0489	0.0259	0.0257
3	0.0358	0.0207	0.0205	0.0396	0.0229	0.0227	0.0382	0.0221	0.0219	0.0392	0.0227	0.0225
4	0.0308	0.0189	0.0186	0.0340	0.0209	0.0206	0.0331	0.0204	0.0200	0.0337	0.0207	0.0204
5	0.0276	0.0178	0.0174	0.0303	0.0195	0.0191	0.0297	0.0192	0.0187	0.0300	0.0193	0.0189
6	0.0252	0.0168	0.0164	0.0277	0.0185	0.0180	0.0274	0.0184	0.0178	0.0274	0.0183	0.0178
8	0.0223	0.0157	0.0152	0.0243	0.0170	0.0166	0.0244	0.0173	0.0167	0.0240	0.0169	0.0164
10	0.0205	0.0151	0.0145	0.0222	0.0162	0.0157	0.0226	0.0168	0.0159	0.0219	0.0160	0.0155

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APPENDIX D.4. Mass Energy-Absorption Coefficients μ_{en}/ρ (cm^2/g) for Various Media[a]

γ-Ray Energy (MeV)	Li	F	LiF	Teflon $(CF_2)_n$	CaF_2	CaF_2:Mn[b]
0.01	0.150	7.61	5.61	6.26	50.7	51.7
0.015	0.0426	2.05	1.51	1.69	15.7	16.1
0.02	0.0205	0.821	0.607	0.674	6.66	6.86
0.03	0.0118	0.233	0.174	0.191	1.96	2.03
0.04	0.0115	0.100	0.0763	0.0833	0.818	0.850
0.05	0.0125	0.0566	0.0448	0.0486	0.419	0.436
0.06	0.0137	0.0391	0.0323	0.0348	0.247	0.256
0.08	0.0159	0.0270	0.0240	0.0254	0.114	0.118
0.10	0.0178	0.0241	0.0224	0.0235	0.0677	0.0697
0.15	0.0210	0.0243	0.0234	0.0243	0.0373	0.0379
0.2	0.0229	0.0256	0.0249	0.0258	0.0315	0.0317
0.3	0.0248	0.0273	0.0266	0.0276	0.0296	0.0296
0.4	0.0255	0.0281	0.0274	0.0284	0.0295	0.0295
0.5	0.0258	0.0282	0.0276	0.0286	0.0293	0.0293
0.6	0.0256	0.0281	0.0274	0.0284	0.0290	0.0290
0.8	0.0250	0.0273	0.0267	0.0277	0.0281	0.0281
1.0	0.0242	0.0264	0.0258	0.0268	0.0271	0.0270
1.5	0.0221	0.0241	0.0236	0.0244	0.0248	0.0247
2.0	0.0203	0.0222	0.0217	0.0225	0.0229	0.0229
3.0	0.0175	0.0196	0.0190	0.0198	0.0205	0.0205
4.0	0.0156	0.0179	0.0173	0.0180	0.0192	0.0192
5.0	0.0142	0.0168	0.0161	0.0169	0.0184	0.0184
6.0	0.0131	0.0160	0.0152	0.0160	0.0179	0.0179
8.0	0.0117	0.0150	0.0141	0.0149	0.0175	0.0175
10.0	0.0107	0.0144	0.0134	0.0143	0.0173	0.0173

[a]Data for Li, F, LiF, and Teflon are taken from Sinclair (1969); those for CaF_2 and CaF_2:Mn are from Attix (1970). Both references were derived from the data of J. H. Hubbell, as published in the review by Evans (1968).
[b]CaF_2:Mn (TLD phosphor) is 49.5% Ca, 48.4% F, and 2.1% Mn by weight.

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APPENDIX E. *(Continued)*

Aluminum

ENERGY	STOPPING POWER COLLISION	STOPPING POWER RADIATIVE	STOPPING POWER TOTAL	CSDA RANGE	RADIATION YIELD	DENS.EFF. CORR. (DELTA)
MeV	MeV cm²/g	MeV cm²/g	MeV cm²/g	g/cm²		
0.0100	1.649E+01	6.559E-03	1.650E+01	3.539E-04	2.132E-04	3.534E-04
0.0125	1.398E+01	6.700E-03	1.398E+01	5.192E-04	2.583E-04	4.937E-04
0.0150	1.220E+01	6.798E-03	1.221E+01	7.111E-04	3.016E-04	6.538E-04
0.0175	1.088E+01	6.871E-03	1.088E+01	9.284E-04	3.435E-04	8.332E-04
0.0200	9.844E+00	6.926E-03	9.851E+00	1.170E-03	3.840E-04	1.031E-03
0.0250	8.338E+00	7.004E-03	8.345E+00	1.724E-03	4.616E-04	1.483E-03
0.0300	7.287E+00	7.059E-03	7.294E+00	2.367E-03	5.353E-04	2.005E-03
0.0350	6.509E+00	7.100E-03	6.516E+00	3.093E-03	6.058E-04	2.593E-03
0.0400	5.909E+00	7.133E-03	5.916E+00	3.900E-03	6.736E-04	3.246E-03
0.0450	5.430E+00	7.162E-03	5.437E+00	4.783E-03	7.390E-04	3.960E-03
0.0500	5.039E+00	7.191E-03	5.046E+00	5.738E-03	8.022E-04	4.732E-03
0.0550	4.714E+00	7.217E-03	4.721E+00	6.763E-03	8.636E-04	5.560E-03
0.0600	4.439E+00	7.243E-03	4.446E+00	7.855E-03	9.232E-04	6.440E-03
0.0700	3.998E+00	7.295E-03	4.005E+00	1.023E-02	1.038E-03	8.351E-03
0.0800	3.661E+00	7.350E-03	3.668E+00	1.284E-02	1.147E-03	1.045E-02
0.0900	3.394E+00	7.411E-03	3.401E+00	1.568E-02	1.252E-03	1.271E-02
0.1000	3.177E+00	7.476E-03	3.185E+00	1.872E-02	1.353E-03	1.513E-02
0.1250	2.781E+00	7.659E-03	2.789E+00	2.714E-02	1.593E-03	2.175E-02
0.1500	2.513E+00	7.865E-03	2.521E+00	3.659E-02	1.816E-03	2.907E-02
0.1750	2.320E+00	8.096E-03	2.328E+00	4.693E-02	2.028E-03	3.694E-02
0.2000	2.174E+00	8.344E-03	2.183E+00	5.804E-02	2.231E-03	4.525E-02
0.2500	1.972E+00	8.888E-03	1.981E+00	8.217E-02	2.616E-03	6.280E-02
0.3000	1.839E+00	9.487E-03	1.849E+00	1.083E-01	2.982E-03	8.116E-02
0.3500	1.747E+00	1.013E-02	1.757E+00	1.361E-01	3.335E-03	9.997E-02
0.4000	1.680E+00	1.082E-02	1.691E+00	1.652E-01	3.678E-03	1.190E-01
0.4500	1.630E+00	1.154E-02	1.642E+00	1.952E-01	4.016E-03	1.380E-01
0.5000	1.592E+00	1.230E-02	1.604E+00	2.260E-01	4.349E-03	1.569E-01
0.5500	1.563E+00	1.309E-02	1.576E+00	2.575E-01	4.680E-03	1.757E-01
0.6000	1.540E+00	1.390E-02	1.554E+00	2.894E-01	5.009E-03	1.943E-01
0.7000	1.507E+00	1.560E-02	1.522E+00	3.545E-01	5.664E-03	2.307E-01
0.8000	1.486E+00	1.739E-02	1.503E+00	4.206E-01	6.319E-03	2.661E-01
0.9000	1.473E+00	1.925E-02	1.492E+00	4.874E-01	6.976E-03	3.005E-01
1.0000	1.465E+00	2.119E-02	1.486E+00	5.546E-01	7.636E-03	3.339E-01
1.2500	1.457E+00	2.630E-02	1.484E+00	7.231E-01	9.306E-03	4.138E-01
1.5000	1.460E+00	3.177E-02	1.491E+00	8.912E-01	1.101E-02	4.898E-01
1.7500	1.466E+00	3.752E-02	1.504E+00	1.058E+00	1.274E-02	5.632E-01
2.0000	1.475E+00	4.350E-02	1.518E+00	1.224E+00	1.449E-02	6.349E-01
2.5000	1.493E+00	5.605E-02	1.549E+00	1.550E+00	1.808E-02	7.757E-01
3.0000	1.510E+00	6.924E-02	1.580E+00	1.869E+00	2.173E-02	9.145E-01
3.5000	1.526E+00	8.292E-02	1.609E+00	2.183E+00	2.544E-02	1.051E+00
4.0000	1.540E+00	9.702E-02	1.637E+00	2.491E+00	2.918E-02	1.183E+00
4.5000	1.552E+00	1.115E-01	1.664E+00	2.794E+00	3.296E-02	1.311E+00
5.0000	1.564E+00	1.263E-01	1.690E+00	3.092E+00	3.675E-02	1.433E+00
5.5000	1.574E+00	1.413E-01	1.715E+00	3.386E+00	4.055E-02	1.550E+00
6.0000	1.583E+00	1.567E-01	1.739E+00	3.675E+00	4.436E-02	1.661E+00
7.0000	1.599E+00	1.879E-01	1.787E+00	4.242E+00	5.197E-02	1.868E+00
8.0000	1.613E+00	2.200E-01	1.833E+00	4.795E+00	5.955E-02	2.055E+00
9.0000	1.625E+00	2.526E-01	1.877E+00	5.334E+00	6.708E-02	2.226E+00
10.0000	1.636E+00	2.858E-01	1.921E+00	5.861E+00	7.454E-02	2.384E+00
12.5000	1.658E+00	3.706E-01	2.029E+00	7.127E+00	9.281E-02	2.727E+00
15.0000	1.676E+00	4.574E-01	2.134E+00	8.328E+00	1.105E-01	3.016E+00
17.5000	1.691E+00	5.459E-01	2.237E+00	9.472E+00	1.275E-01	3.265E+00
20.0000	1.704E+00	6.357E-01	2.340E+00	1.056E+01	1.438E-01	3.484E+00
25.0000	1.726E+00	8.180E-01	2.544E+00	1.261E+01	1.745E-01	3.857E+00
30.0000	1.743E+00	1.003E+00	2.746E+00	1.450E+01	2.027E-01	4.168E+00
35.0000	1.757E+00	1.190E+00	2.947E+00	1.626E+01	2.287E-01	4.435E+00
40.0000	1.769E+00	1.379E+00	3.148E+00	1.790E+01	2.528E-01	4.669E+00
45.0000	1.780E+00	1.569E+00	3.349E+00	1.944E+01	2.751E-01	4.878E+00
50.0000	1.789E+00	1.761E+00	3.550E+00	2.089E+01	2.959E-01	5.068E+00
55.0000	1.797E+00	1.953E+00	3.751E+00	2.226E+01	3.152E-01	5.241E+00
60.0000	1.805E+00	2.147E+00	3.951E+00	2.356E+01	3.333E-01	5.401E+00
70.0000	1.818E+00	2.535E+00	4.353E+00	2.597E+01	3.662E-01	5.687E+00
80.0000	1.829E+00	2.927E+00	4.755E+00	2.817E+01	3.953E-01	5.938E+00
90.0000	1.838E+00	3.320E+00	5.158E+00	3.019E+01	4.214E-01	6.161E+00

APPENDIX E. *(Continued)*

Calcium Fluoride

ENERGY	STOPPING POWER COLLISION	STOPPING POWER RADIATIVE	STOPPING POWER TOTAL	CSDA RANGE	RADIATION YIELD	DENS.EFF. CORR. (DELTA)
MeV	MeV cm²/g	MeV cm²/g	MeV cm²/g	g/cm²		
0.0100	1.666E+01	7.284E-03	1.667E+01	3.503E-04	2.300E-04	0.0
0.0125	1.412E+01	7.499E-03	1.413E+01	5.139E-04	2.809E-04	0.0
0.0150	1.233E+01	7.657E-03	1.233E+01	7.039E-04	3.301E-04	0.0
0.0175	1.099E+01	7.778E-03	1.099E+01	9.190E-04	3.778E-04	0.0
0.0200	9.945E+00	7.874E-03	9.953E+00	1.158E-03	4.243E-04	0.0
0.0250	8.424E+00	8.016E-03	8.432E+00	1.706E-03	5.138E-04	0.0
0.0300	7.363E+00	8.118E-03	7.371E+00	2.343E-03	5.993E-04	0.0
0.0350	6.577E+00	8.197E-03	6.585E+00	3.062E-03	6.813E-04	0.0
0.0400	5.970E+00	8.263E-03	5.979E+00	3.860E-03	7.604E-04	0.0
0.0450	5.487E+00	8.319E-03	5.495E+00	4.733E-03	8.368E-04	0.0
0.0500	5.093E+00	8.370E-03	5.101E+00	5.678E-03	9.109E-04	0.0
0.0550	4.764E+00	8.416E-03	4.773E+00	6.693E-03	9.829E-04	0.0
0.0600	4.486E+00	8.458E-03	4.495E+00	7.773E-03	1.053E-03	0.0
0.0700	4.041E+00	8.541E-03	4.050E+00	1.012E-02	1.188E-03	0.0
0.0800	3.701E+00	8.621E-03	3.709E+00	1.271E-02	1.316E-03	0.0
0.0900	3.432E+00	8.704E-03	3.440E+00	1.551E-02	1.440E-03	0.0
0.1000	3.213E+00	8.788E-03	3.222E+00	1.851E-02	1.559E-03	0.0
0.1250	2.814E+00	9.016E-03	2.823E+00	2.684E-02	1.840E-03	0.0
0.1500	2.544E+00	9.265E-03	2.553E+00	3.617E-02	2.102E-03	0.0
0.1750	2.349E+00	9.534E-03	2.359E+00	4.638E-02	2.350E-03	0.0
0.2000	2.203E+00	9.821E-03	2.213E+00	5.733E-02	2.586E-03	0.0
0.2500	2.000E+00	1.045E-02	2.011E+00	8.111E-02	3.033E-03	0.0
0.3000	1.867E+00	1.113E-02	1.878E+00	1.069E-01	3.455E-03	5.037E-03
0.3500	1.774E+00	1.187E-02	1.786E+00	1.342E-01	3.859E-03	1.737E-02
0.4000	1.706E+00	1.266E-02	1.719E+00	1.628E-01	4.252E-03	3.256E-02
0.4500	1.656E+00	1.348E-02	1.669E+00	1.923E-01	4.638E-03	5.026E-02
0.5000	1.617E+00	1.435E-02	1.631E+00	2.226E-01	5.017E-03	7.003E-02
0.5500	1.587E+00	1.525E-02	1.602E+00	2.536E-01	5.394E-03	9.144E-02
0.6000	1.563E+00	1.618E-02	1.579E+00	2.850E-01	5.768E-03	1.141E-01
0.7000	1.528E+00	1.812E-02	1.547E+00	3.491E-01	6.512E-03	1.623E-01
0.8000	1.506E+00	2.016E-02	1.526E+00	4.142E-01	7.256E-03	2.128E-01
0.9000	1.491E+00	2.229E-02	1.513E+00	4.800E-01	8.002E-03	2.645E-01
1.0000	1.481E+00	2.450E-02	1.505E+00	5.463E-01	8.752E-03	3.167E-01
1.2500	1.470E+00	3.034E-02	1.500E+00	7.128E-01	1.065E-02	4.459E-01
1.5000	1.468E+00	3.658E-02	1.505E+00	8.793E-01	1.258E-02	5.700E-01
1.7500	1.471E+00	4.313E-02	1.515E+00	1.045E+00	1.456E-02	6.875E-01
2.0000	1.477E+00	4.995E-02	1.527E+00	1.209E+00	1.656E-02	7.980E-01
2.5000	1.491E+00	6.423E-02	1.555E+00	1.534E+00	2.065E-02	9.994E-01
3.0000	1.506E+00	7.922E-02	1.585E+00	1.852E+00	2.481E-02	1.178E+00
3.5000	1.520E+00	9.476E-02	1.615E+00	2.165E+00	2.903E-02	1.338E+00
4.0000	1.533E+00	1.108E-01	1.644E+00	2.472E+00	3.328E-02	1.482E+00
4.5000	1.545E+00	1.272E-01	1.673E+00	2.773E+00	3.755E-02	1.614E+00
5.0000	1.557E+00	1.439E-01	1.701E+00	3.070E+00	4.183E-02	1.735E+00
5.5000	1.567E+00	1.610E-01	1.728E+00	3.361E+00	4.611E-02	1.848E+00
6.0000	1.577E+00	1.783E-01	1.755E+00	3.649E+00	5.038E-02	1.953E+00
7.0000	1.594E+00	2.137E-01	1.808E+00	4.210E+00	5.889E-02	2.144E+00
8.0000	1.610E+00	2.499E-01	1.859E+00	4.755E+00	6.732E-02	2.316E+00
9.0000	1.623E+00	2.868E-01	1.910E+00	5.286E+00	7.566E-02	2.472E+00
10.0000	1.635E+00	3.243E-01	1.959E+00	5.803E+00	8.388E-02	2.615E+00
12.5000	1.660E+00	4.199E-01	2.079E+00	7.041E+00	1.039E-01	2.931E+00
15.0000	1.679E+00	5.180E-01	2.197E+00	8.210E+00	1.231E-01	3.203E+00
17.5000	1.695E+00	6.177E-01	2.313E+00	9.319E+00	1.415E-01	3.442E+00
20.0000	1.709E+00	7.189E-01	2.428E+00	1.037E+01	1.590E-01	3.656E+00
25.0000	1.731E+00	9.243E-01	2.655E+00	1.234E+01	1.917E-01	4.026E+00
30.0000	1.748E+00	1.133E+00	2.881E+00	1.415E+01	2.217E-01	4.338E+00
35.0000	1.762E+00	1.344E+00	3.106E+00	1.582E+01	2.491E-01	4.609E+00
40.0000	1.774E+00	1.557E+00	3.331E+00	1.738E+01	2.742E-01	4.848E+00
45.0000	1.784E+00	1.771E+00	3.555E+00	1.883E+01	2.974E-01	5.061E+00
50.0000	1.793E+00	1.987E+00	3.780E+00	2.019E+01	3.189E-01	5.253E+00
55.0000	1.802E+00	2.204E+00	4.005E+00	2.148E+01	3.388E-01	5.429E+00
60.0000	1.809E+00	2.422E+00	4.231E+00	2.269E+01	3.574E-01	5.590E+00
70.0000	1.822E+00	2.860E+00	4.682E+00	2.494E+01	3.909E-01	5.878E+00
80.0000	1.833E+00	3.301E+00	5.134E+00	2.698E+01	4.205E-01	6.130E+00
90.0000	1.843E+00	3.744E+00	5.587E+00	2.884E+01	4.468E-01	6.353E+00

APPENDIX E. *(Continued)*

Water (Liquid)

ENERGY	STOPPING POWER COLLISION	STOPPING POWER RADIATIVE	STOPPING POWER TOTAL	CSDA RANGE	RADIATION YIELD	DENS.EFF. CORR. (DELTA)
MeV	MeV cm²/g	MeV cm²/g	MeV cm²/g	g/cm²		
0.0100	2.256E+01	3.898E-03	2.257E+01	2.515E-04	9.408E-05	0.0
0.0125	1.897E+01	3.927E-03	1.898E+01	3.728E-04	1.133E-04	0.0
0.0150	1.647E+01	3.944E-03	1.647E+01	5.147E-04	1.316E-04	0.0
0.0175	1.461E+01	3.955E-03	1.461E+01	6.761E-04	1.492E-04	0.0
0.0200	1.317E+01	3.963E-03	1.318E+01	8.566E-04	1.663E-04	0.0
0.0250	1.109E+01	3.974E-03	1.110E+01	1.272E-03	1.990E-04	0.0
0.0300	9.653E+00	3.984E-03	9.657E+00	1.756E-03	2.301E-04	0.0
0.0350	8.592E+00	3.994E-03	8.596E+00	2.306E-03	2.599E-04	0.0
0.0400	7.777E+00	4.005E-03	7.781E+00	2.919E-03	2.886E-04	0.0
0.0450	7.130E+00	4.018E-03	7.134E+00	3.591E-03	3.165E-04	0.0
0.0500	6.603E+00	4.031E-03	6.607E+00	4.320E-03	3.435E-04	0.0
0.0550	6.166E+00	4.046E-03	6.170E+00	5.103E-03	3.698E-04	0.0
0.0600	5.797E+00	4.062E-03	5.801E+00	5.940E-03	3.955E-04	0.0
0.0700	5.207E+00	4.098E-03	5.211E+00	7.762E-03	4.452E-04	0.0
0.0800	4.757E+00	4.138E-03	4.762E+00	9.773E-03	4.931E-04	0.0
0.0900	4.402E+00	4.181E-03	4.407E+00	1.196E-02	5.393E-04	0.0
0.1000	4.115E+00	4.228E-03	4.120E+00	1.431E-02	5.841E-04	0.0
0.1250	3.591E+00	4.355E-03	3.596E+00	2.083E-02	6.912E-04	0.0
0.1500	3.238E+00	4.494E-03	3.242E+00	2.817E-02	7.926E-04	0.0
0.1750	2.984E+00	4.643E-03	2.988E+00	3.622E-02	8.894E-04	0.0
0.2000	2.793E+00	4.801E-03	2.798E+00	4.487E-02	9.826E-04	0.0
0.2500	2.528E+00	5.141E-03	2.533E+00	6.372E-02	1.161E-03	0.0
0.3000	2.355E+00	5.514E-03	2.360E+00	8.421E-02	1.331E-03	0.0
0.3500	2.235E+00	5.913E-03	2.241E+00	1.060E-01	1.496E-03	0.0
0.4000	2.148E+00	6.339E-03	2.154E+00	1.288E-01	1.658E-03	0.0
0.4500	2.083E+00	6.787E-03	2.090E+00	1.523E-01	1.818E-03	0.0
0.5000	2.034E+00	7.257E-03	2.041E+00	1.766E-01	1.976E-03	0.0
0.5500	1.995E+00	7.747E-03	2.003E+00	2.013E-01	2.134E-03	1.103E-02
0.6000	1.963E+00	8.254E-03	1.972E+00	2.265E-01	2.292E-03	2.938E-02
0.7000	1.917E+00	9.312E-03	1.926E+00	2.778E-01	2.608E-03	7.435E-02
0.8000	1.886E+00	1.043E-02	1.896E+00	3.302E-01	2.928E-03	1.267E-01
0.9000	1.864E+00	1.159E-02	1.876E+00	3.832E-01	3.251E-03	1.835E-01
1.0000	1.849E+00	1.280E-02	1.862E+00	4.367E-01	3.579E-03	2.428E-01
1.2500	1.829E+00	1.600E-02	1.845E+00	5.717E-01	4.416E-03	3.944E-01
1.5000	1.822E+00	1.942E-02	1.841E+00	7.075E-01	5.281E-03	5.437E-01
1.7500	1.821E+00	2.303E-02	1.844E+00	8.432E-01	6.171E-03	6.866E-01
2.0000	1.824E+00	2.678E-02	1.850E+00	9.785E-01	7.085E-03	8.218E-01
2.5000	1.834E+00	3.468E-02	1.868E+00	1.247E+00	8.969E-03	1.069E+00
3.0000	1.846E+00	4.299E-02	1.889E+00	1.514E+00	1.092E-02	1.288E+00
3.5000	1.858E+00	5.164E-02	1.910E+00	1.777E+00	1.291E-02	1.484E+00
4.0000	1.870E+00	6.058E-02	1.931E+00	2.037E+00	1.495E-02	1.660E+00
4.5000	1.882E+00	6.976E-02	1.951E+00	2.295E+00	1.702E-02	1.821E+00
5.0000	1.892E+00	7.917E-02	1.971E+00	2.550E+00	1.911E-02	1.967E+00
5.5000	1.902E+00	8.876E-02	1.991E+00	2.802E+00	2.123E-02	2.102E+00
6.0000	1.911E+00	9.854E-02	2.010E+00	3.052E+00	2.336E-02	2.227E+00
7.0000	1.928E+00	1.185E-01	2.047E+00	3.545E+00	2.766E-02	2.453E+00
8.0000	1.943E+00	1.391E-01	2.082E+00	4.030E+00	3.200E-02	2.652E+00
9.0000	1.956E+00	1.601E-01	2.116E+00	4.506E+00	3.636E-02	2.831E+00
10.0000	1.968E+00	1.814E-01	2.149E+00	4.975E+00	4.072E-02	2.992E+00
12.5000	1.993E+00	2.362E-01	2.230E+00	6.117E+00	5.163E-02	3.341E+00
15.0000	2.014E+00	2.926E-01	2.306E+00	7.219E+00	6.243E-02	3.633E+00
17.5000	2.031E+00	3.501E-01	2.381E+00	8.286E+00	7.309E-02	3.885E+00
20.0000	2.046E+00	4.086E-01	2.454E+00	9.320E+00	8.355E-02	4.107E+00
25.0000	2.070E+00	5.277E-01	2.598E+00	1.130E+01	1.039E-01	4.487E+00
30.0000	2.089E+00	6.489E-01	2.738E+00	1.317E+01	1.233E-01	4.806E+00
35.0000	2.105E+00	7.716E-01	2.876E+00	1.496E+01	1.418E-01	5.082E+00
40.0000	2.118E+00	8.955E-01	3.013E+00	1.665E+01	1.594E-01	5.326E+00
45.0000	2.129E+00	1.021E+00	3.150E+00	1.828E+01	1.762E-01	5.544E+00
50.0000	2.139E+00	1.146E+00	3.286E+00	1.983E+01	1.923E-01	5.741E+00
55.0000	2.148E+00	1.273E+00	3.421E+00	2.132E+01	2.076E-01	5.921E+00
60.0000	2.156E+00	1.400E+00	3.556E+00	2.276E+01	2.222E-01	6.087E+00
70.0000	2.170E+00	1.656E+00	3.827E+00	2.547E+01	2.496E-01	6.383E+00
80.0000	2.182E+00	1.914E+00	4.096E+00	2.799E+01	2.747E-01	6.641E+00
90.0000	2.193E+00	2.173E+00	4.366E+00	3.035E+01	2.978E-01	6.871E+00