GEORGIA INSTITUTE OF TECHNOLOGY

The George W. Woodruff School of Mechanical Engineering

Ph.D. Qualifier Exam

Fall Semester 2002

__________________ Your ID Code

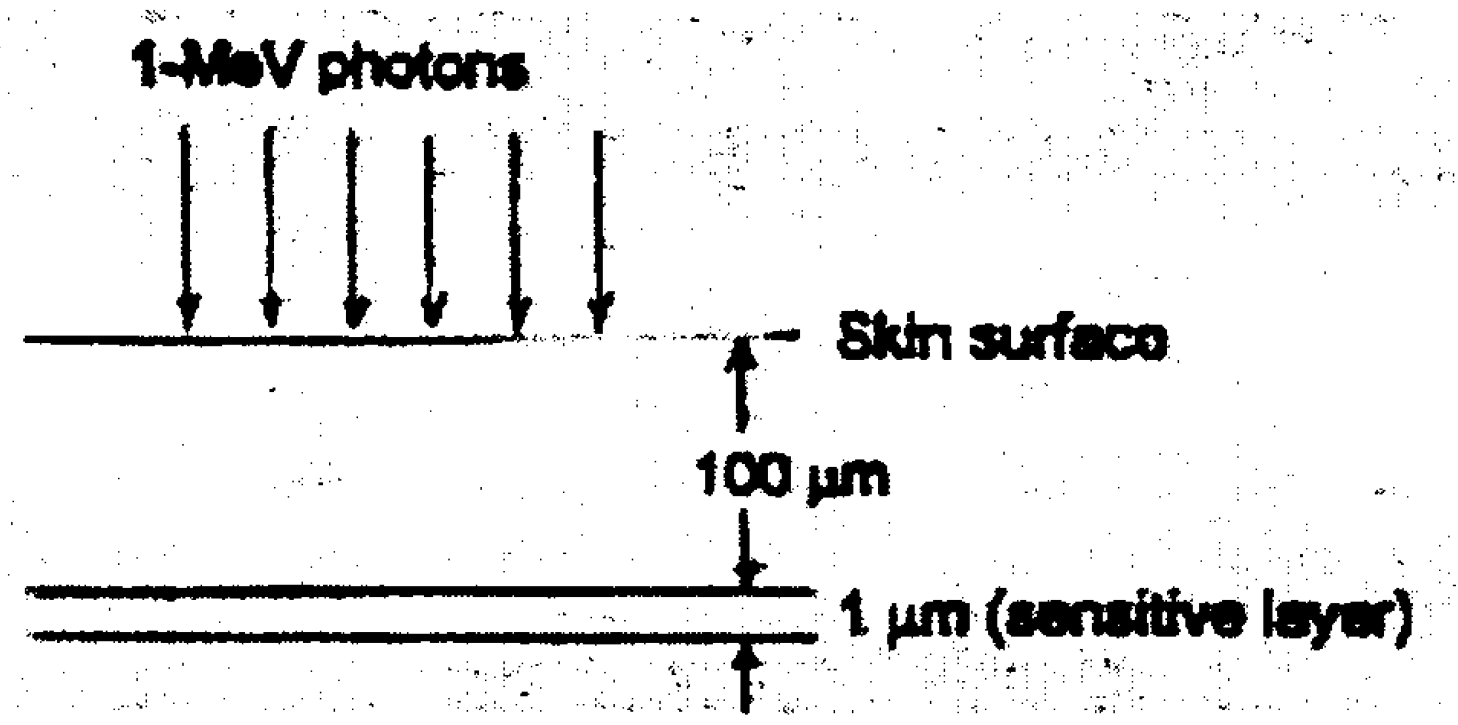
Radiation Protection

Instructions

1. Use a separate page for each answer sheet (no front to back answers).
2. The question number should be shown on each answer sheet.
3. ANSWER 4 OF 6 QUESTIONS ONLY.
4. Staple your question sheet to your answer sheets and turn in.

RADIATION PROTECTION

1. Refer to the figure below, assume the sensitive layer of the skin is 1 μm thick and is located at 100 μm below the surface. If the surface of the skin is perpendicularly irradiated by a broad beam of 1-MeV gamma photons with a total fluence of 1.0×10^9 photons cm^{-2}, use the Attachment to estimate the collisional kerma and the absorbed dose respectively for the sensitive layer of the skin.



2. The effect of radiation on biological cells is often expressed by the linear-quadratic formula $\alpha D+\beta D^2$.
   (a) Provide the biophysical mechanisms associated with each term (i.e. αD and βD^2) of the formula.
   (b) Use the formula to express the effect of neutrons and gamma-rays separately, and then derive the algebraic expression of the relative biological effectiveness (RBE) of neutron versus gamma rays. Use your derivation to explain why the RBE of neutrons is often much greater than 1.

3. (a) List two different measurement methods that are routinely used to monitor radiation workers for the internally deposited radionuclides.
   (b) Describe each method and explain how the quantity of an internally-deposited radionuclide can be obtained by the method.

Photon Energy (MeV)	Air [(cm²/g)]			Water			ICRU Compact Bone [(cm²/g)]			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

APPENDIX D.3. (*Continued*)

Photon Energy (MeV)	Polystyrene			Methyl Methacrylate, Lucite, Plexiglas, Perspex			Polyethylene			Pyrex glass		
	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	2.17	1.82	1.82	3.31	2.91	2.91	2.04	1.69	1.69	17.1	16.5	16.5
0.015	0.764	0.495	0.495	1.07	0.783	0.783	0.737	0.461	0.461	5.11	4.75	4.75
0.02	0.429	0.193	0.193	0.555	0.310	0.310	0.425	0.180	0.180	2.24	1.94	1.94
0.03	0.261	0.0562	0.0562	0.300	0.0899	0.0899	0.268	0.0535	0.0535	0.785	0.554	0.554
0.04	0.216	0.0300	0.0300	0.233	0.0437	0.0437	0.225	0.0295	0.0295	0.430	0.232	0.232
0.05	0.197	0.0236	0.0236	0.205	0.0301	0.0301	0.207	0.0238	0.0238	0.299	0.122	0.122
0.06	0.186	0.0218	0.0218	0.191	0.0254	0.0254	0.196	0.0225	0.0225	0.241	0.0768	0.0768
0.08	0.173	0.0217	0.0217	0.176	0.0232	0.0232	0.183	0.0228	0.0228	0.190	0.0428	0.0428
0.10	0.164	0.0231	0.0231	0.165	0.0238	0.0238	0.173	0.0243	0.0243	0.166	0.0325	0.0325
0.15	0.145	0.0263	0.0263	0.146	0.0266	0.0266	0.154	0.0279	0.0279	0.139	0.0274	0.0274
0.2	0.132	0.0286	0.0286	0.133	0.0287	0.0287	0.140	0.0303	0.0303	0.125	0.0276	0.0276
0.3	0.115	0.0309	0.0309	0.115	0.0310	0.0310	0.122	0.0328	0.0328	0.107	0.0289	0.0289
0.4	0.103	0.0318	0.0318	0.103	0.0318	0.0318	0.109	0.0337	0.0337	0.0953	0.0295	0.0295
0.5	0.0937	0.0321	0.0321	0.0939	0.0322	0.0322	0.0994	0.0340	0.0340	0.0868	0.0297	0.0297
0.6	0.0867	0.0319	0.0318	0.0869	0.0319	0.0319	0.0919	0.0338	0.0337	0.0801	0.0295	0.0294
0.8	0.0761	0.0311	0.0310	0.0763	0.0312	0.0311	0.0807	0.0330	0.0329	0.0704	0.0288	0.0287
1.0	0.0683	0.0300	0.0300	0.0686	0.0302	0.0301	0.0725	0.0319	0.0319	0.0633	0.0279	0.0277
1.5	0.0557	0.0275	0.0275	0.0559	0.0276	0.0275	0.0591	0.0292	0.0291	0.0515	0.0254	0.0252
2	0.0476	0.0253	0.0252	0.0478	0.0254	0.0253	0.0505	0.0268	0.0267	0.0444	0.0235	0.0233
3	0.0381	0.0221	0.0219	0.0383	0.0222	0.0220	0.0403	0.0234	0.0232	0.0360	0.0209	0.0207
4	0.0326	0.0200	0.0198	0.0329	0.0202	0.0199	0.0345	0.0211	0.0209	0.0314	0.0194	0.0190
5	0.0289	0.0185	0.0182	0.0292	0.0187	0.0184	0.0303	0.0195	0.0192	0.0284	0.0184	0.0179
6	0.0263	0.0174	0.0171	0.0266	[illegible]	[illegible]	[illegible]	[illegible]				

A-150 Tissue-Equivalent Plastic

ENERGY MeV	STOPPING POWER COLLISION MeV cm²/g	STOPPING POWER RADIATIVE MeV cm²/g	STOPPING POWER TOTAL MeV cm²/g	CSDA RANGE g/cm²	RADIATION YIELD	DENS. EFF. CORR. (DELTA)
0.0100	2.294E+01	3.196E-03	2.295E+01	2.463E-04	7.329E-05	0.0
0.0125	1.927E+01	3.174E-03	1.927E+01	3.657E-04	9.048E-05	0.0
0.0150	1.671E+01	3.180E-03	1.671E+01	5.054E-04	1.059E-04	0.0
0.0175	1.482E+01	3.197E-03	1.482E+01	6.646E-04	1.191E-04	0.0
0.0200	1.335E+01	3.205E-03	1.336E+01	8.426E-04	1.327E-04	0.0
0.0250	1.124E+01	3.219E-03	1.124E+01	1.253E-03	1.588E-04	0.0
0.0300	9.769E+00	3.232E-03	9.772E+00	1.731E-03	1.838E-04	0.0
0.0350	8.691E+00	3.245E-03	8.694E+00	2.275E-03	2.079E-04	0.0
0.0400	7.863E+00	3.258E-03	7.866E+00	2.880E-03	2.311E-04	0.0
0.0450	7.206E+00	3.273E-03	7.209E+00	3.549E-03	2.537E-04	0.0
0.0500	6.671E+00	3.287E-03	6.675E+00	4.267E-03	2.756E-04	0.0
0.0550	6.228E+00	3.302E-03	6.231E+00	5.043E-03	2.971E-04	0.0
0.0600	5.853E+00	3.319E-03	5.857E+00	5.871E-03	3.180E-04	0.0
0.0700	5.256E+00	3.352E-03	5.259E+00	7.677E-03	3.586E-04	0.0
0.0800	4.800E+00	3.388E-03	4.803E+00	9.669E-03	3.977E-04	0.0
0.0900	4.441E+00	3.427E-03	4.444E+00	1.184E-02	4.356E-04	0.0
0.1000	4.150E+00	3.467E-03	4.153E+00	1.417E-02	4.723E-04	0.0
0.1250	3.620E+00	3.578E-03	3.623E+00	2.064E-02	5.602E-04	0.0
0.1500	3.262E+00	3.697E-03	3.265E+00	2.792E-02	6.438E-04	0.0
0.1750	3.005E+00	3.824E-03	3.009E+00	3.592E-02	7.234E-04	0.0
0.2000	2.812E+00	3.959E-03	2.816E+00	4.452E-02	8.003E-04	0.0
0.2500	2.544E+00	4.247E-03	2.548E+00	6.325E-02	9.476E-04	0.0
0.3000	2.369E+00	4.563E-03	2.373E+00	8.362E-02	1.089E-03	0.0
0.3500	2.247E+00	4.901E-03	2.252E+00	1.053E-01	1.226E-03	0.0
0.4000	2.156E+00	5.260E-03	2.161E+00	1.280E-01	1.361E-03	2.969E-02
0.4500	2.086E+00	5.639E-03	2.092E+00	1.515E-01	1.495E-03	6.284E-02
0.5000	2.033E+00	6.036E-03	2.039E+00	1.757E-01	1.628E-03	9.751E-02
0.5500	1.991E+00	6.448E-03	1.997E+00	2.005E-01	1.761E-03	1.337E-01
0.6000	1.957E+00	6.875E-03	1.964E+00	2.258E-01	1.895E-03	1.708E-01
0.7000	1.908E+00	7.768E-03	1.915E+00	2.774E-01	2.164E-03	2.464E-01
0.8000	1.874E+00	8.706E-03	1.883E+00	3.300E-01	2.436E-03	3.223E-01
0.9000	1.851E+00	9.687E-03	1.860E+00	3.835E-01	2.711E-03	3.975E-01
1.0000	1.834E+00	1.071E-02	1.845E+00	4.375E-01	2.990E-03	4.712E-01
1.2500	1.812E+00	1.341E-02	1.825E+00	5.739E-01	3.705E-03	6.472E-01
1.5000	1.803E+00	1.630E-02	1.819E+00	7.111E-01	4.447E-03	8.100E-01
1.7500	1.802E+00	1.934E-02	1.821E+00	8.485E-01	5.209E-03	9.601E-01
2.0000	1.804E+00	2.252E-02	1.827E+00	9.856E-01	5.992E-03	1.099E+00
2.5000	1.814E+00	2.920E-02	1.843E+00	1.258E+00	7.609E-03	1.346E+00
3.0000	1.827E+00	3.625E-02	1.863E+00	1.528E+00	9.281E-03	1.561E+00
3.5000	1.839E+00	4.358E-02	1.883E+00	1.795E+00	1.100E-02	1.751E+00
4.0000	1.852E+00	5.116E-02	1.903E+00	2.059E+00	1.275E-02	1.922E+00
4.5000	1.863E+00	5.896E-02	1.922E+00	2.320E+00	1.453E-02	2.077E+00
5.0000	1.874E+00	6.695E-02	1.941E+00	2.579E+00	1.633E-02	2.218E+00
5.5000	1.884E+00	7.511E-02	1.959E+00	2.836E+00	1.816E-02	2.349E+00
6.0000	1.894E+00	8.341E-02	1.977E+00	3.090E+00	2.000E-02	2.470E+00
7.0000	1.911E+00	1.004E-01	2.011E+00	3.591E+00	2.372E-02	2.691E+00
8.0000	1.926E+00	1.179E-01	2.044E+00	4.084E+00	2.748E-02	2.887E+00
9.0000	1.939E+00	1.358E-01	2.075E+00	4.570E+00	3.127E-02	3.064E+00
10.0000	1.951E+00	1.540E-01	2.105E+00	5.048E+00	3.508E-02	3.227E+00
12.5000	1.975E+00	2.007E-01	2.176E+00	6.216E+00	4.461E-02	3.582E+00
15.0000	1.995E+00	2.488E-01	2.243E+00	7.340E+00	5.411E-02	3.885E+00
17.5000	2.010E+00	2.979E-01	2.308E+00	8.446E+00	6.352E-02	4.150E+00
20.0000	2.024E+00	3.478E-01	2.372E+00	9.515E+00	7.282E-02	4.385E+00
25.0000	2.046E+00	4.496E-01	2.495E+00	1.157E+01	9.097E-02	4.788E+00
30.0000	2.063E+00	5.532E-01	2.616E+00	1.353E+01	1.085E-01	5.126E+00
35.0000	2.077E+00	6.582E-01	2.735E+00	1.540E+01	1.253E-01	5.417E+00
40.0000	2.089E+00	7.643E-01	2.854E+00	1.718E+01	1.414E-01	5.671E+00
45.0000	2.100E+00	8.714E-01	2.971E+00	1.890E+01	1.569E-01	5.897E+00
50.0000	2.109E+00	9.792E-01	3.089E+00	2.055E+01	1.717E-01	6.101E+00
55.0000	2.118E+00	1.088E+00	3.205E+00	2.214E+01	1.860E-01	6.286E+00
60.0000	2.125E+00	1.197E+00	3.322E+00	2.367E+01	1.996E-01	6.456E+00
70.0000	2.139E+00	1.416E+00	3.555E+00	2.658E+01	2.254E-01	6.758E+00
80.0000	2.151E+00	1.638E+00	3.788E+00	2.931E+01	2.491E-01	7.020E+00
90.0000	2.161E+00	1.860E+00	4.021E+00	3.187E+01	2.712E-01	7.253E+00

Skeletal Muscle (ICRP)

ENERGY MeV	STOPPING POWER COLLISION MeV cm²/g	STOPPING POWER RADIATIVE MeV cm²/g	STOPPING POWER TOTAL MeV cm²/g	CSDA RANGE g/cm²	RADIATION YIELD	DENS. EFF. CORR. (DELTA)
0.0100	2.231E+01	3.833E-03	2.231E+01	2.343E-04	[illegible]	0.0
0.0125	1.876E+01	3.863E-03	1.877E+01	3.771E-04	[illegible]	0.0
0.0150	1.628E+01	3.880E-03	1.629E+01	5.203E-04	[illegible]	0.0
0.0175	1.443E+01	3.892E-03	1.443E+01	6.838E-04	[illegible]	0.0
0.0200	1.303E+01	3.901E-03	1.303E+01	8.682E-04	[illegible]	0.0
0.0250	1.097E+01	3.913E-03	1.098E+01	1.286E-03	[illegible]	0.0
0.0300	9.547E+00	3.924E-03	9.551E+00	1.776E-03	[illegible]	0.0
0.0350	8.498E+00	3.934E-03	8.502E+00	2.332E-03	[illegible]	0.0
0.0400	7.692E+00	3.946E-03	7.696E+00	2.951E-03	2.874E-04	0.0
0.0450	7.052E+00	3.957E-03	7.056E+00	3.631E-03	3.131E-04	0.0
0.0500	6.531E+00	3.973E-03	6.535E+00	4.368E-03	3.421E-04	0.0
0.0550	6.099E+00	3.986E-03	6.102E+00	5.160E-03	[illegible]	0.0
0.0600	5.733E+00	4.004E-03	5.737E+00	6.006E-03	[illegible]	0.0
0.0700	5.151E+00	4.040E-03	5.155E+00	7.848E-03	[illegible]	0.0
0.0800	4.706E+00	4.079E-03	4.710E+00	9.881E-03	[illegible]	0.0
0.0900	4.355E+00	4.122E-03	4.359E+00	1.209E-02	[illegible]	0.0
0.1000	4.071E+00	4.168E-03	4.075E+00	1.447E-02	[illegible]	0.0
0.1250	3.552E+00	4.291E-03	3.557E+00	2.098E-02	[illegible]	0.0
0.1500	3.203E+00	4.431E-03	3.207E+00	2.835E-02	[illegible]	0.0
0.1750	2.951E+00	4.577E-03	2.955E+00	3.643E-02	[illegible]	0.0
0.2000	2.763E+00	4.734E-03	2.768E+00	4.537E-02	[illegible]	0.0
0.2500	2.501E+00	5.070E-03	2.506E+00	6.492E-02	[illegible]	0.0
0.3000	2.329E+00	5.438E-03	2.335E+00	8.313E-02	[illegible]	0.0
0.3500	2.211E+00	5.832E-03	2.216E+00	1.071E-01	1.492E-03	0.0
0.4000	2.125E+00	6.252E-03	2.131E+00	1.302E-01	1.653E-03	0.0
0.4500	2.061E+00	6.694E-03	2.068E+00	1.540E-01	1.812E-03	0.0
0.5000	2.012E+00	7.158E-03	2.019E+00	1.785E-01	1.970E-03	[illegible]
0.5500	1.972E+00	7.642E-03	1.980E+00	2.035E-01	2.128E-03	[illegible]
0.6000	1.941E+00	8.141E-03	1.949E+00	2.290E-01	2.285E-03	[illegible]
0.7000	1.895E+00	9.186E-03	1.904E+00	2.809E-01	2.602E-03	[illegible]
0.8000	1.863E+00	1.028E-02	1.874E+00	3.339E-01	2.921E-03	[illegible]
0.9000	1.842E+00	1.143E-02	1.853E+00	3.876E-01	3.244E-03	[illegible]
1.0000	1.827E+00	1.262E-02	1.839E+00	4.418E-01	3.571E-03	[illegible]
1.2500	1.806E+00	1.578E-02	1.822E+00	5.784E-01	4.406E-03	[illegible]
1.5000	1.799E+00	1.918E-02	1.818E+00	7.150E-01	5.272E-03	[illegible]
1.7500	1.799E+00	2.271E-02	1.821E+00	8.532E-01	6.162E-03	[illegible]
2.0000	1.801E+00	2.642E-02	1.828E+00	9.903E-01	7.076E-03	[illegible]
2.5000	1.812E+00	3.421E-02	1.846E+00	1.263E+00	8.956E-03	[illegible]
3.0000	1.824E+00	4.241E-02	1.866E+00	1.532E+00	[illegible]	[illegible]
3.5000	1.836E+00	5.095E-02	1.887E+00	1.798E+00	[illegible]	[illegible]
4.0000	1.848E+00	5.977E-02	1.908E+00	2.062E+00	1.493E-02	[illegible]
4.5000	1.860E+00	6.883E-02	1.928E+00	2.323E+00	1.699E-02	[illegible]
5.0000	1.870E+00	7.811E-02	1.948E+00	2.580E+00	1.908E-02	[illegible]
5.5000	1.880E+00	8.758E-02	1.968E+00	2.836E+00	2.119E-02	[illegible]
6.0000	1.889E+00	9.722E-02	1.987E+00	3.089E+00	2.332E-02	[illegible]
7.0000	1.906E+00	1.170E-01	2.023E+00	3.587E+00	2.761E-02	[illegible]
8.0000	1.921E+00	1.372E-01	2.058E+00	4.077E+00	3.196E-02	[illegible]
9.0000	1.934E+00	1.579E-01	2.092E+00	4.559E+00	3.629E-02	[illegible]
10.0000	1.946E+00	1.790E-01	2.125E+00	5.033E+00	4.065E-02	[illegible]
12.5000	1.971E+00	2.331E-01	2.205E+00	6.188E+00	5.152E-02	[illegible]
15.0000	1.992E+00	2.887E-01	2.281E+00	7.303E+00	6.231E-02	[illegible]
17.5000	2.009E+00	3.455E-01	2.354E+00	8.382E+00	[illegible]	[illegible]
20.0000	2.023E+00	4.032E-01	2.427E+00	9.428E+00	[illegible]	[illegible]
25.0000	2.047E+00	5.208E-01	2.568E+00	1.143E+01	1.037E-01	[illegible]
30.0000	2.066E+00	6.403E-01	2.706E+00	1.333E+01	1.230E-01	[illegible]
35.0000	2.081E+00	7.615E-01	2.842E+00	1.513E+01	1.415E-01	[illegible]
40.0000	2.094E+00	8.838E-01	2.978E+00	1.685E+01	1.592E-01	[illegible]
45.0000	2.105E+00	1.007E+00	3.112E+00	1.849E+01	1.760E-01	[illegible]
50.0000	2.115E+00	1.131E+00	3.247E+00	2.006E+01	1.920E-01	[illegible]
55.0000	2.124E+00	1.256E+00	3.380E+00	2.157E+01	2.073E-01	[illegible]
60.0000	2.132E+00	1.382E+00	3.514E+00	2.302E+01	2.219E-01	[illegible]
70.0000	2.146E+00	1.635E+00	3.780E+00	2.577E+01	2.492E-01	[illegible]
80.0000	2.158E+00	1.889E+00	4.047E+00	2.832E+01	2.745E-01	[illegible]
90.0000	2.168E+00	2.145E+00	4.313E+00	3.071E+01	2.974E-01	[illegible]

4. A terrorist wants to mail a ^{90}Sr source to a U.S. Senator to create a panic among congressman. The terrorist places plastic sheets of material (density = 0.9 g/cm^3) around the source to shield it from detection en route to the Senate building. The strontium is in powder form.
   (a) How thick does he make the plastic to range out the strontium beta rays?
   (b) Not being a health physicist, he doesn't realize that the ^{90}Y progeny is in secular equilibrium with the strontium. What fraction of the ^{90}Y dose is attenuated by the plastic sheets?
   (c) If the letter (ignore attenuation by the paper of the envelope) passes within 2 cm in air of a beta-sensitive detector with its alarm level set at 10 microgray per hour, will the alarm go off. Assume 10 mCi of ^{90}Sr was loaded in the envelope by the terrorist.

Data: See attached sheets.

Isotope	$E_{\beta,max}$ **(MeV)**	**Half Life**
Sr-90	0.546	28.79 years
Y-90	2.281	64 hours

TABLE C.10—*Absorbed dose rates from beta and conversion electron emitters in an infinite water medium. $\dot{D}(r)$ is the dose rate ($nGy \cdot h^{-1}$) at r (cm) from a 1 Bq point isotropic source. The third column for each nuclide gives the dose rate from a uniform plane source of 1 $Bq \cdot cm^{-2}$ (Cross et al., 1992c)*

^{14}C			^{32}P			^{56}Mn			^{60}Co		
r	$r^2\dot{D}(r)$	Plane Source	r	$r^2\dot{D}(r)$	Plane Source	r	$r^2\dot{D}(r)$	Plane Source	r	$r^2\dot{D}(r)$	Plane Source
.000	611.5	∞	.000	106.4	∞	.00	119.3	∞	.0000	407.3	∞
.001	373.7	3429	.006	104.5	2473	.01	110.5	2086	.0006	294.8	4757
.002	304.3	2009	.012	105.0	2035	.02	107.5	1629	.0012	268.1	3578
.003	252.3	1310	.018	105.5	1770	.03	104.8	1363	.0018	251.2	2926
.004	209.9	895	.024	105.8	1581	.04	101.8	1177	.0024	238.4	2486
.005	174.7	626	.030	106.0	1433	.05	98.9	1037	.0030	227.3	2161
.006	144.7	444	.060	105.3	990	.10	83.5	655	.0060	186.6	1294
.007	119.2	316	.090	102.5	729	.15	70.4	462	.0090	157.4	862
.008	97.5	226	.120	98.0	549	.20	60.9	344	.0120	133.6	601
.009	79.0	160	.150	92.0	417	.25	54.3	263	.0150	113.4	428
.010	63.4	113	.180	84.8	316	.30	49.4	204	.0180	95.8	309
.011	50.2	79	.210	76.6	238	.35	45.2	159	.0210	80.4	224
.012	39.2	55	.240	67.7	177	.40	41.2	122	.0240	66.9	162
.013	30.2	37	.270	58.7	130	.45	36.9	93	.0270	55.2	117
.014	22.8	25	.300	49.7	95	.50	32.5	70	.0300	45.0	84
.015	16.8	16	.330	41.2	67	.55	28.1	52	.0330	36.2	60
.016	12.2	11	.360	33.4	47	.60	23.8	38	.0360	28.7	42
.017	8.6	7	.390	26.3	32	.65	19.6	27	.0390	22.4	29
.018	5.9	4	.420	20.2	21	.70	15.8	19	.0420	17.2	20
.019	3.9	2	.450	15.0	14	.75	12.4	13	.0450	13.0	13
.020	2.5	1	.480	10.7	8	.80	9.4	8	.0480	9.6	9
.021	1.5		.510	7.3	5	.85	6.9	5	.0510	6.9	6
.022	.9		.540	4.8	3	.90	4.9	3	.0540	4.8	3
.023	.5		.570	3.0	1	.95	3.3	2	.0570	3.3	2
.024	.3		.600	1.7		.00	2.1	1	.0600	2.1	1
.025	.1		.630	.9		.05	1.3		.0630	1.3	
.026	.0		.660	.4		.10	.7		.0660	.8	
			.690	.2		.15	.4		.0690	.5	
						.20	.2		.0720	.2	
									.0750	.1	

^{89}Sr			^{90}Sr			^{90}Y			^{91}Y		
r	$r^2\dot{D}(r)$	Plane Source	r	$r^2\dot{D}(r)$	Plane Source	r	$r^2\dot{D}(r)$	Plane Source	r	$r^2\dot{D}(r)$	Plane Source
.000	125.8	∞	.0000	239.8	∞	.000	104.0	∞	.000	124.5	∞
.005	114.1	2507	.0008	195.9	4186	.008	99.6	2343	.005	113.0	2513
.010	111.9	2034	.0016	185.7	3386	.016	99.2	1927	.010	110.9	2044
.015	110.5	1754	.0024	179.0	2928	.024	98.9	1678	.015	109.5	1767
.020	109.3	1557	.0032	174.2	2611	.032	98.6	1501	.020	108.3	1572
.025	108.2	1405	.0040	170.3	2371	.040	98.3	1363	.025	107.3	1421
.050	103.1	963	.0048	166.8	2178	.080	96.4	956	.050	102.4	982
.075	97.8	710	.0056	163.7	2018	.120	93.5	717	.075	97.5	731
.100	92.1	540	.0064	161.0	1882	.160	89.7	552	.100	92.2	560
.125	86.1	416	.0072	158.5	1764	.200	85.1	430	.125	86.7	436
.150	79.8	321	.0080	156.1	1660	.240	79.6	336	.150	80.8	340
.175	73.1	247	.0160	138.1	1044	.280	73.6	262	.175	74.5	265
.200	65.9	189	.0240	123.3	716	.320	67.1	203	.200	67.8	205
.225	58.5	143	.0320	109.6	506	.360	60.4	156	.225	60.8	158
.250	50.9	107	.0400	96.5	363	.400	53.5	119	.250	53.7	120
.275	43.5	78	.0480	83.7	260	.440	46.6	89	.275	46.6	90
.300	36.4	56	.0560	71.4	185	.480	39.7	65	.300	39.7	66
.325	29.8	40	.0640	59.6	130	.520	33.2	47	.325	33.1	48
.350	23.7	27	.0720	48.7	90	.560	27.0	33	.350	27.0	34
.375	18.3	18	.0800	38.9	61	.600	21.3	22	.375	21.5	24
.400	13.7	12	.0880	30.1	40	.640	16.3	15	.400	16.6	16
.425	9.9	7	.0960	22.7	26	.680	12.0	9	.425	12.5	10
.450	6.8	4	.1040	16.4	16	.720	8.5	6	.450	9.0	6
.475	4.4	2	.1120	11.4	9	.760	5.7	3	.475	6.2	4
.500	2.7	1	.1200	7.6	5	.800	3.6	2	.500	4.1	2
.525	1.6		.1280	4.8	3	.840	2.2	1	.525	2.5	1
.550	.8		.1360	2.8	1	.880	1.2		.550	1.5	
.575	.4		.1440	1.5		.920	.6		.575	.8	
.600	.2		.1520	.8		.960	.2		.600	.4	
			.1600	.3					.625	.2	

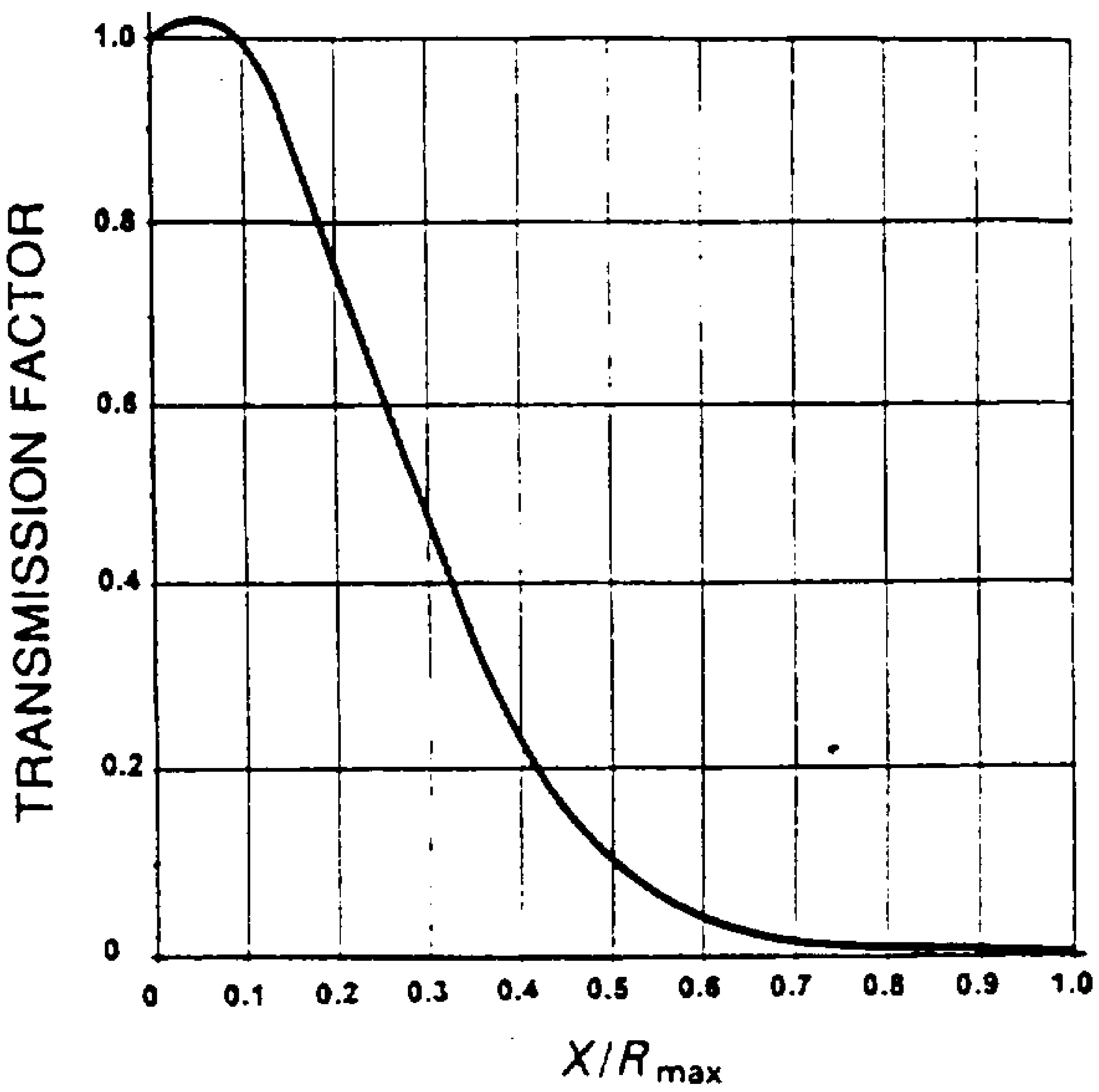


Fig. 8.9. Transmission factor as a function of x/R_{max} for the estimation of the dose $H'(x)$ behind the layer thickness x of a material, produced by beta rays with the maximum range R_{max} (Piesch *et al.*, 1983)

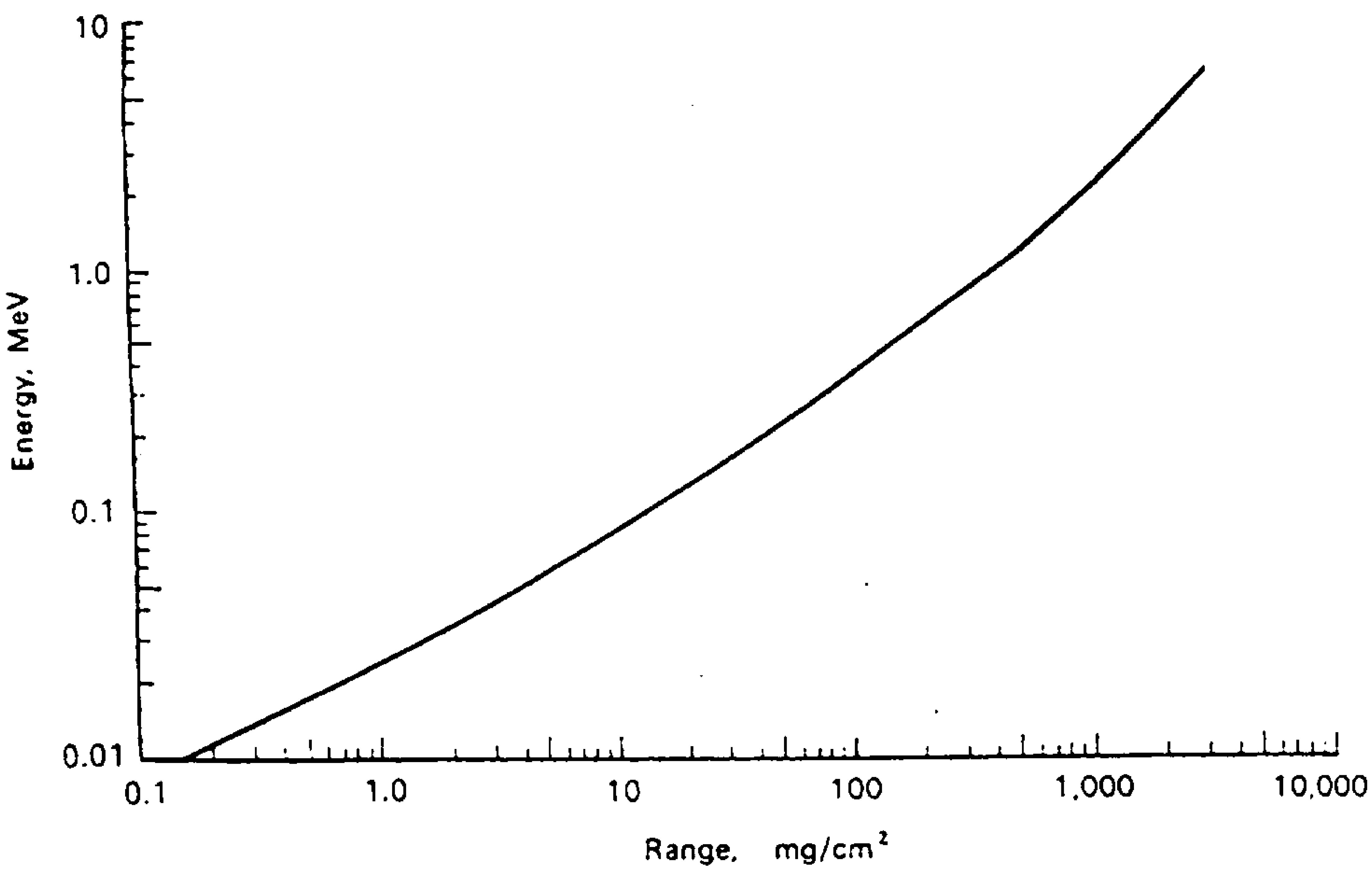
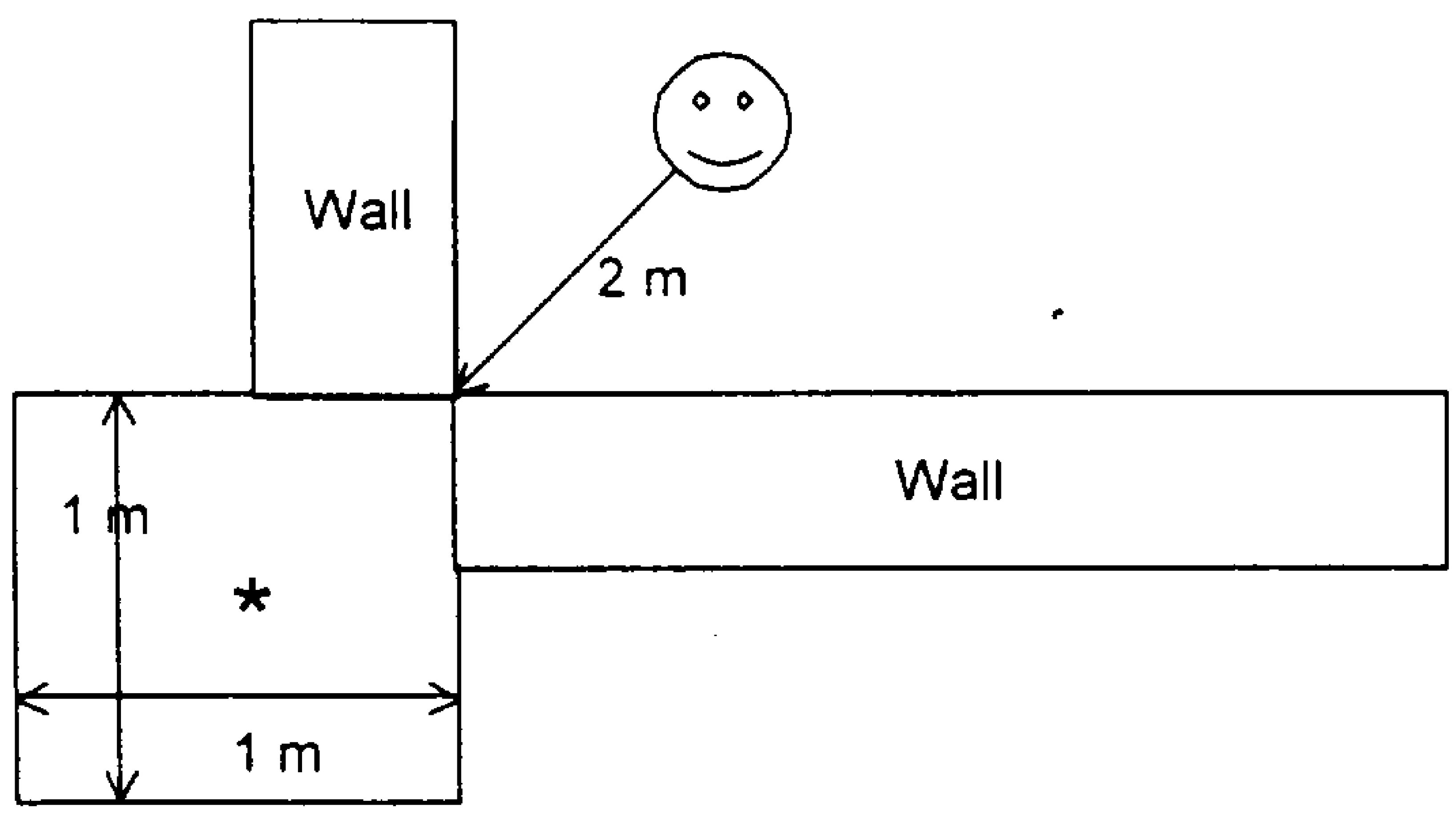


FIGURE 5.4. Range-energy curve for beta particles. The range is expressed in units of density thickness (From *Radiological Health Handbook*. Office of Technical Services, Washington. D.C..

5. A sinister, university radiation safety officer Dr. Notso Nice does not want to pay the fee to dispose of a 5 Ci Co-60 source. Unfortunately, a new building is being constructed on his campus and he throws the source into a concrete column as it is being poured. The source (almost magically) is in the center of the concrete column. The column has a 1 m x 1 m square cross section. Once the building is completed, a graduate student spends 20 hours a week at a distance of 2 m from a corner of the column. What exposure does the student receive in one year from this source?



Data: Concrete Density = 2.35 g/cm2

Co-60 emits two gamma rays per decay (1.117 and 1.332 MeV)

Use the Berger form of the Buildup Factor.

E (MeV)	Concrete μ/ρ (cm^2/g)	Tissue μ_{en}/ρ (cm^2/g)	Air μ/ρ (cm^2/g)	*a*	*b*
1.0	0.0636	0.0310	0.0636	1.45	0.034
1.5	0.0518	0.0283	0.0516	1.14	0.021

6. The useful beam of a diagnostic x-ray machine is directed 50% of the time at a 5-inch thick hard-brick wall that is 4 ft away. The machine operates at 200 kVp and a current of 200 mA for an average of 5 minutes a day, 5 days a week. An uncontrolled corridor is on the other side of the wall.
   (a) What thickness of lead has to be added to make the wall an adequate primary barrier for the x-rays?
   (b) With the additional shielding from part (a) in place, the procedures performed with the machine change so that the primary beam is always directed toward this wall. Without adding still more shielding, what would be the maximum workload permitted, all other factors being the same?

Table 10.1. Occupancy Factors

Full occupancy $T = 1$	Control space, wards, workrooms, darkrooms, corridors large enough to hold desks, waiting rooms, rest rooms used by occupationally exposed personnel, children's play areas, living quarters, occupied space in adjacent buildings
Partial occupancy $T = 1/4$	Corridors too narrow for desks, utility rooms, rest rooms not used routinely by occupationally exposed personnel, elevators run by operators, and uncontrolled parking lots
Occasional occupancy $T = 1/16$	Stairways, automatic elevators, outside areas used only for pedestrians or vehicular traffic, closets too small for future workrooms, toilets not used routinely by occupationally exposed personnel

Table 10.2. Half-Value and Tenth-Value Layers[a]

	Attenuation Material					
	Lead, mm		Concrete, cm		Iron, cm	
Peak Voltage (kV)	*HVL*	*TVL*	*HVL*	*TVL*	*HVL*	*TVL*
50	0.06	0.17	0.43	1.5		
70	0.17	0.52	0.84	2.8		
100	0.27	0.88	1.6	5.3		
125	0.28	0.93	2.0	6.6		
150	0.30	0.99	2.24	7.4		
200	0.52	1.7	2.5	8.4		
250	0.88	2.9	2.8	9.4		
300	1.47	4.8	3.1	10.4		
400	2.5	8.3	3.3	10.9		
500	3.6	11.9	3.6	11.7		
1,000	7.9	26	4.4	14.7		
2,000	12.5	42	6.4	21		
3,000	14.5	48.5	7.4	24.5		
4,000	16	53	8.8	29.2	2.7	9.1
6,000	16.9	56	10.4	34.5	3.0	9.9
8,000	16.9	56	11.4	37.8	3.1	10.3
10,000	16.6	55	11.9	39.6	3.2	10.5
Cesium-137	6.5	21.6	4.8	15.7	1.6	5.3
Cobalt-60	12	40	6.2	20.6	2.1	6.9
Radium	16.6	55	6.9	23.4	2.2	7.4

[a] Approximate values obtained at high attenuation for the indicated peak voltages under broad beam conditions; with low attenuation these values will be significantly less. (From NCRP 49. By permission.)

TABLE 10.4. **Densities of Commerical Building Materials**

Material	Density range, g/cm³	Density of average sample, g/cm³
Brick	1.6–2.5	1.9
Granite	2.60–2.70	2.63
Limestone	1.87–2.69	2.30
Marble	2.47–2.86	2.70
Sandplaster	—	1.54
Sandstone	1.90–2.69	2.20
Siliceous concrete	2.25–2.40	2.35
Tile	1.6–2.5	1.9

TABLE 10.5. **Commercial Lead Sheets**

Thickness		Nominal weight	
mm	in.	#/ft²	kg/m²
0.79	1/32	2	10
1.00	5/128	2½	12
1.19	3/64	3	15
1.58	1/16	4	20
1.98	5/64	5	24
2.38	3/32	6	29
3.17	1/8	8	39
4.76	3/16	12	59
6.35	1/4	16	78
8.50	1/3	20	98
10.1	2/5	24	117
12.7	1/2	30	146
16.9	2/3	40	195
25.4	1	60	293

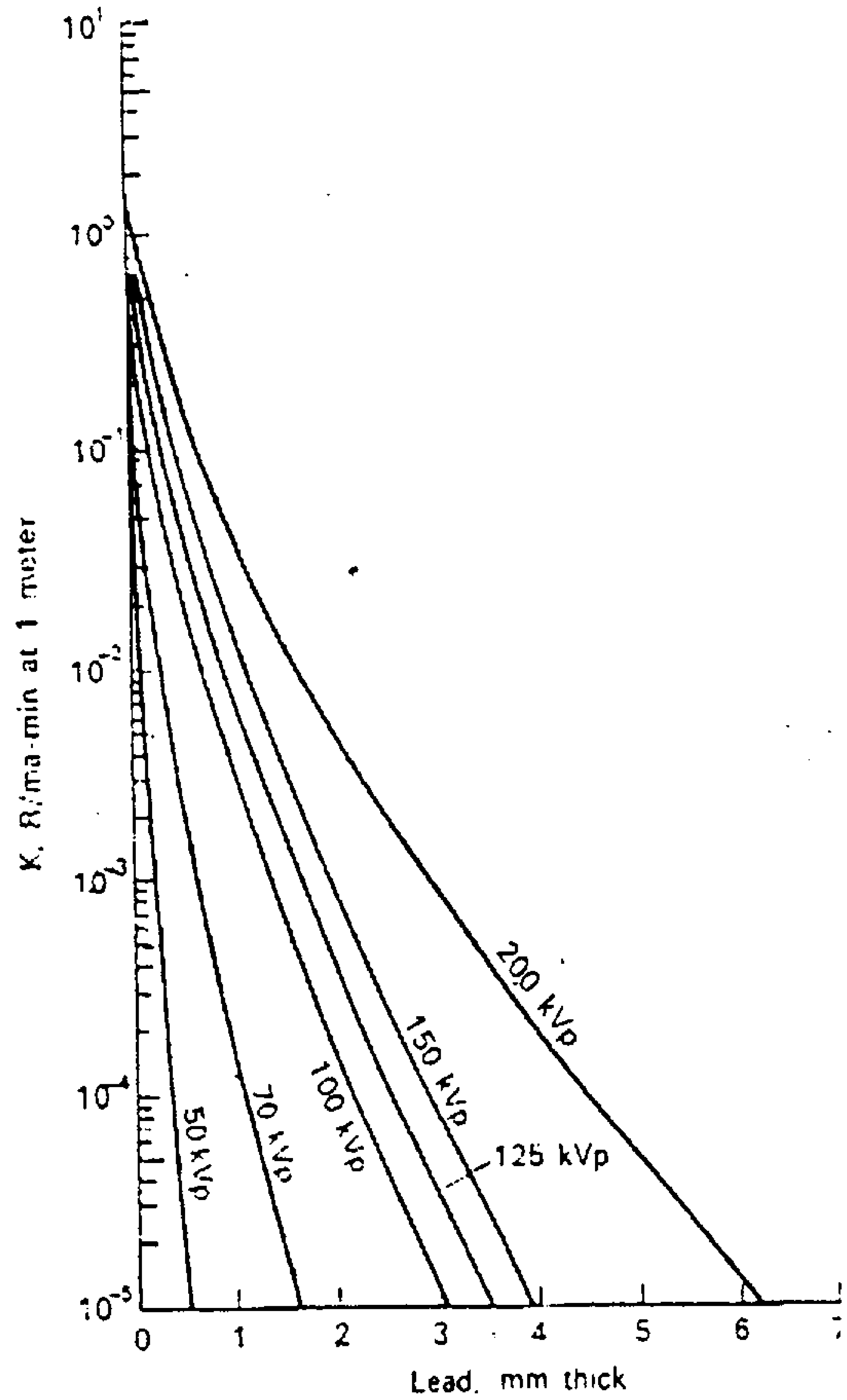


FIGURE 10.12. Broad-beam attenuation in lead of X-rays produced by potentials of 50 to 200 kV peak. The measurements were made with a 90° angle between the electron beam and the axis of the pulsed wave form X-ray beam. The 50-, 70-, 100-, and 125-kVp X-rays were filtered with 0.5-mm aluminum; the 150- and 200-kVp X-rays were filtered with 3-mm aluminum. (From *Radiological Health Handbook*, 1970.)

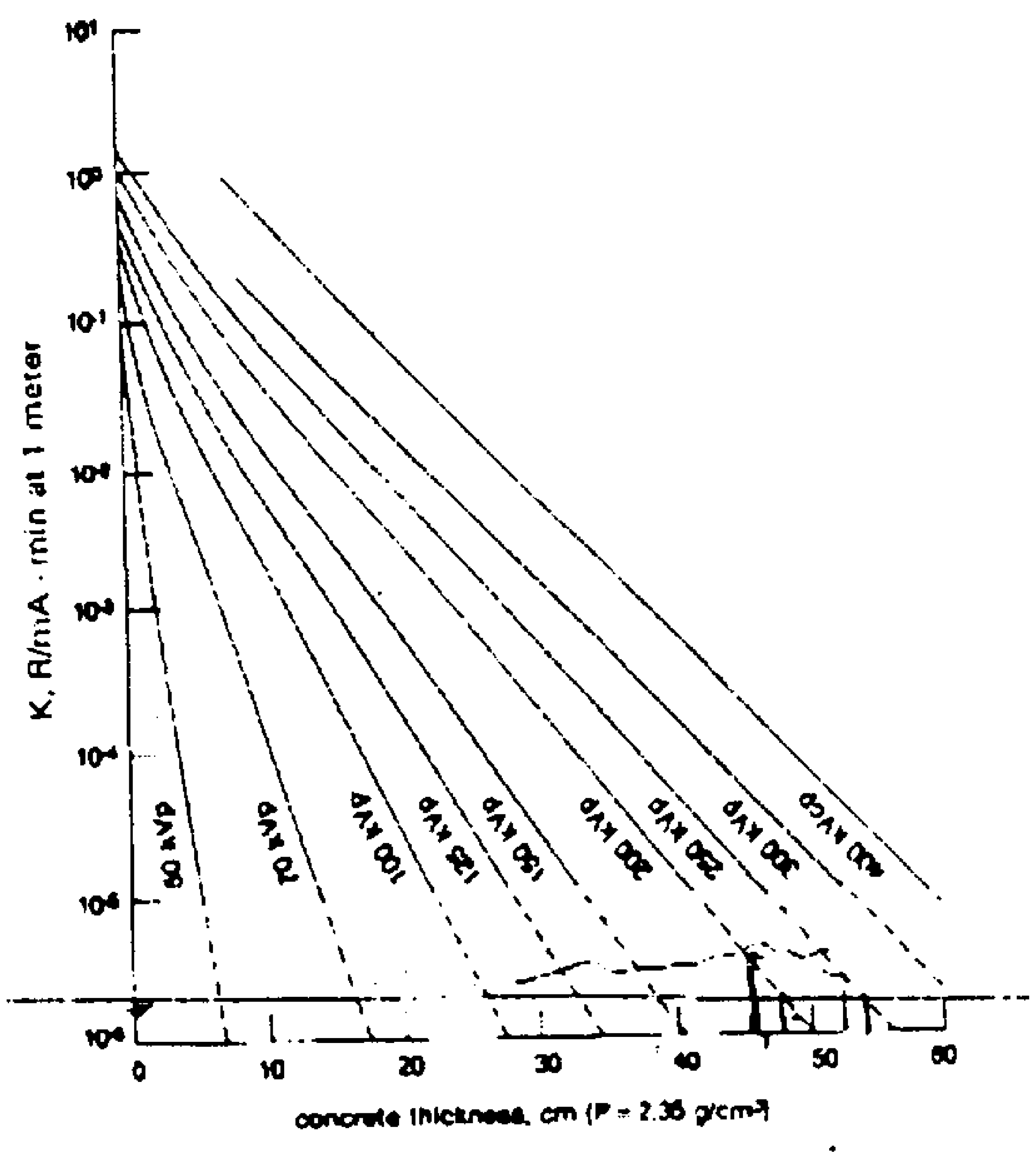


FIGURE 10.13. Attenuation in concrete of X-rays produced by potentials of 50 to 300 kVp; 400 kV constant potential. The measurements were made with a 90° angle between the electron beam and the axis of the X-ray beam. The curves for 50 to 300 kV are for a pulsed waveform. The filtrations were 1 mm Al for 50 kV, 1.5 mm Al for 70 kV, 2 mm Al for 100 kV, and 3 mm Al for 125, 150, 200, 250, and 300 kV. The 400-kV curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm Cu. (From NCRP Report No. 49, *Structural Shielding Design and Evaluation for Medical Use of X-Rays and Gamma Rays of Energies up to 10 MeV*, 1976. Full-size reproductions of the figures giving barrier requirements are available from the NCRP as an adjunct to the report. By permission.)