Engineering Compendium on Radiation Shielding

Prepared by numerous specialists

Edited by R. G. Jaeger Editor-in-Chief
E. P. Blizard †, A. B. Chilton,
M. Grotenhuis, A. Hönig, Th. A. Jaeger
H. H. Eisenlohr Coordinating Editor

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With the publication of Volume II, "Shielding Materials", the *Engineering Compendium on Radiation Shielding* has been completed. More than ten years of work resulted in a publication which summarizes the present state of the art in the very complex field of radiation shielding. More than a hundred specialists have contributed to this endeavour by making available to the shielding workers their experience and knowledge, and by collecting relevant data scattered around in many hundreds of journals and reports. The IAEA and the editors hope that the Compendium will be a valuable source of information to the user and that it will serve as a reliable guide to all those engaged in shielding problems. They wish to extend their sincere gratitude to all authors for their cooperation, in particular to Prof. H. E. HUNGERFORD for his most valuable and unselfish assistance without which, publication of this volume would have been further delayed. They also wish to express their appreciation of the excellent work and of the patience shown by the staff of Springer-Verlag.

Horst H. Eisenlohr
IAEA, Department of Research and Isotopes
Coordinating Editor

Preface

The utilization of nuclear energy makes great demands on the knowledge of the engineers engaged in design work and calculations relating to construction in nuclear industry. Apart, of course, from nuclear reactors themselves, a great deal of nuclear experience is involved in the design and construction of radiotherapy centres, non-destructive testing laboratories, particle accelerators, radioisotope laboratories and nuclear research plants.

Whereas in the USA there appears to be no great difference in the methods of training personnel for fundamental or for applied science, European universities draw a sharp dividing line between the two fields. However, if we consider graduates solely from the point of view of their activities at their place of employment, two types of personnel can be distinguished: scientifically oriented research workers and those with a more technical and practical background who are looking for rational and rapid methods and solutions, even at some expense in terms of accuracy.

The *Engineering Compendium on Radiation Shielding* endeavours to cover both approaches, the scientific and the technical. Volume I was devoted to the fundamental aspects of shielding, while Volumes II and III discuss its technology.

The present volume bears the title *Shielding Materials* and constitutes the ninth chapter of the Compendium. It covers the nuclear, physical and mechanical properties of shielding materials. The materials are described in the first two sections from the points of view of gamma radiation shielding alone and of combined neutron and gamma radiation shielding. It has not been possible for the editors to maintain this division without some compromise, although the editor of Volume II has made every effort to comply with the original intentions. Even though their physical properties make heavy elements not really suitable for neutron shielding, these properties have been included since heavy elements are often used in combination with other materials for the construction of protective shielding and nuclear reactor walls.

The third section of the book discusses laminated shields, while the last two sections present the effects of high temperatures on the relevant properties of concrete, and discuss the question of the proper choice of shielding materials.

This second volume of the three-volume work has been published last. Its later publication was caused partly by the great difficulty experienced in obtaining realistic figures, which are treated as classified data in a number of countries, and partly by the fact that the cooperation of the authors in some chapters was impeded by problems of technical translation.

The editor would like to express his sincere thanks to the representatives of Springer-Verlag for their helpfulness and cooperation. Their patience, which often went far beyond that usually called for in publishing, is gratefully acknowledged.

Brno, March 1975

Arnost Hönig
Editor of Volume II

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Chapter 9

SHIELDING MATERIALS

9.1. MATERIALS AGAINST GAMMA RAYS

9.1.1. LEAD AND LEAD ALLOYS

by E. E. HAMER and A. E. MCARTHY

9.1.1.1. INTRODUCTION

Pure lead is a soft, structurally weak, low melting point (327.4 °C) material with a density of 11.34 g/cm^3; it is an excellent attenuator of gamma radiation. Normally, alloying reduces the density and therefore its shielding effectiveness, but the structural properties are significantly improved. Lead is attractive as a shielding material against gamma radiation because of its low cost-to-density ratio, the variety of forms available, and the numerous fabrication methods that can be used.

9.1.1.2. OCCURRENCE AND EXTRACTION

The earth's crust is calculated to be about 0.0016% lead. The only ore of commercial importance is galena (PbS), which is usually found associated with iron, zinc, and silver minerals. Secondary lead is presently recovered in tonnage that is about equivalent to primary lead production. Lead has a high salvage value because of its good resistance to corrosion and the comparative ease with which it may be recovered from scrap materials by smelting and refining processes [1].

9.1.1.3. PROPERTIES

A. Nuclear Properties

Tables 9.1.–1 and –2 compares thicknesses and weights of lead and five other materials for equivalent gamma-ray shielding.

Table 4.1.–3 (Vol. I, p. 175) lists values of the gamma ray mass-attenuation coefficient μ/ϱ [cm^2/g]; Table 4.1.–9 (Vol. I, p. 183) lists values of the mass energy-transfer coefficient μ_K/ϱ, and the mass energy-absorption coefficient, μ_{en}/ϱ.

Figures 9.1.–1 and –2 and Table 9.1.–3 show the exposure-attenuation factors for broad-beam gamma radiation of a point isotropic source in lead for various energies of incident gamma radiation as a function of the lead thickness [3].

The exposure-attenuation factor K can be used to obtain the gamma radiation dose rate I from a point isotropic source through a specified thickness of shielding r in accordance with the equation

$$K = I/I_0 = B\,e^{-\mu r},$$

where

I_0 gamma ray dose rate for an unshielded point isotropic source at the specified distance,

B Taylor buildup factor for the material thickness being considered and the photon energy of the radiation source,

μ attenuation coefficient of the shield material for the source radiation [cm^{-1}].

Figures 9.1.–3 through –18 show the shield (exposure)-attenuation factor, α_i, for the radiation dose rate as a function of the lead shield thickness for a large number of radioisotopes and certain isotope combinations [4]. Included are curves (Fig. 9.1.–18) for mixed fission products (MFP-)

Table 9.1.–1. Equivalent thicknesses of various materials per unit lead thickness, for 5 and 10 mean free paths of lead, for several gamma-ray energies [2][a])

Energy [MeV]	Iron		Water		Concrete	
	$(\mu t)_{Pb} = 5$	$(\mu t)_{Pb} = 10$	$(\mu t)_{Pb} = 5$	$(\mu t)_{Pb} = 10$	$(\mu t)_{Pb} = 5$	$(\mu t)_{Pb} = 10$
0.10	21.0	—	—	—	—	—
0.5	3.9	3.6	32.8	27.8	—	—
1.0	2.2	2.1	16.0	14.3	7.2	6.6
2.0	1.8	1.7	12.5	11.6	5.6	5.4
3.0	1.8	1.8	13.3	12.5	5.9	5.7
4.0	1.9	1.9	15.0	14.2	6.7	6.4
5.0	2.1	2.0	17.1	15.9	7.5	7.2
6.0	2.3	2.1	19.3	17.9	8.5	8.0
7.0	2.4	2.3	21.6	19.9	9.4	8.8
8.0	2.5	2.3	23.8	21.9	10.0	9.4

[a]) Differences in equivalent thicknesses over 5 and 10 mean free paths is attributable to differences in buildup-factor ratios for 5 and 10 mean free paths. Multiply any given lead thickness by the values given in the table to obtain the equivalent thickness of iron, water, and concrete.

Table 9.1.–2. Comparison of gamma attenuation properties of various materials by thickness and weight [1]

Buildup of lower energy radiation not taken into account.
(1 lb/sq. ft = 4.882 kg/m²· 1 lb/cu. ft = 16.02 kg/m³)

1. Relative thickness

Material	Density [lbs/cu. ft]	Shield thickness [ft] 0.2 MeV	0.5 MeV	1.0 MeV	3.0 MeV
Concrete	144	2.5	4.1	5.4	9.1
Heavy concrete	288	1.13	2.05	2.7	4.55
Iron	450	0.7	1.26	1.75	2.91
Lead	707	0.071	0.44	0.95	1.63
Tungsten	1200	0.054	0.30	0.60	0.985
Uranium	1170	0.038	0.22	0.52	0.91

Slabs of these thicknesses will attenuate radiation by 10^{10}, i. e., for a spherical source 1 foot in radius, radiation 10 feet from center of source is attenuated by 10^{12}.

2. Effect of geometry on weight

Material	Shield weight in pounds							
	0.2 MeV		0.5 MeV		1.0 MeV		3.0 MeV	
	A	B	A	B	A	B	A	B
Concrete	380	22 500	590	79 200	780	157 100	1310	619 000
Heavy concrete	325	10 150	590	32 900	780	59 900	1310	205 000
Iron	315	7 370	568	19 900	780	37 600	1310	111 000
Lead	50	68	310	5 880	670	19 000	1150	50 900
Tungsten	65	814	360	6 010	720	15 540	1180	34 200
Uranium	45	76	255	3 990	605	12 290	1070	29 200

Column A gives lbs/sq. ft of slab perpendicular to radiation; Column B gives total weight of spherical shield. Thickness as above.

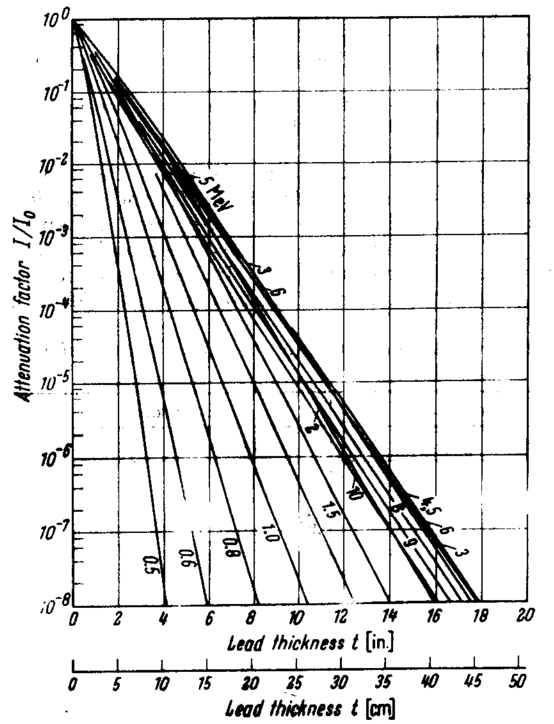

Fig. 9.1.–1. Exposure attenuation factors I/I_0, for broad-beam gamma radiation of a point isotropic source in lead ($\varrho = 11340$ kg/m³) in dependence on the energy of incident gamma radiation, E_0 [3].

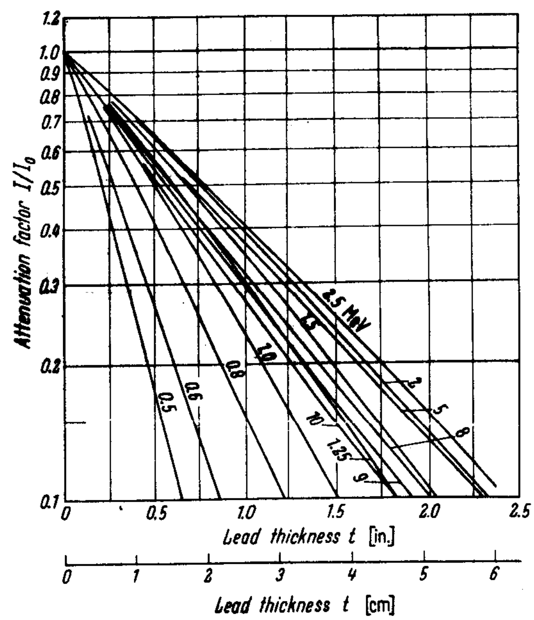

Fig. 9.1.–2. Exposure attenuation factors I/I_0, for broad-beam gamma radiation of a point isotropic source in lead ($\varrho = 11340$ kg/m³) in dependence on the energy of incident gamma radiation, E_0 [3].

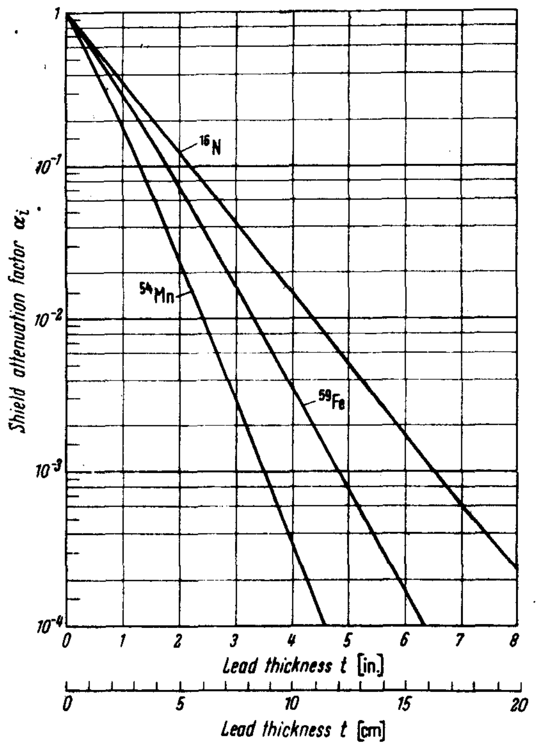

Fig. 9.1.–3. Radiation dose rate shield attenuation factor for ^{16}N, ^{54}Mn and ^{59}Fe as a function of lead shield thickness [4].

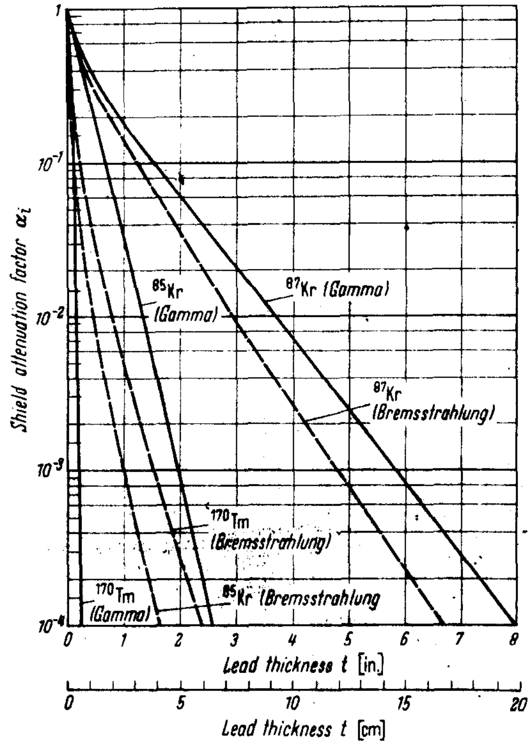

Fig. 9.1.–5. Radiation dose rate shield attenuation factor for ^{85}Kr, ^{87}Kr and ^{170}Tm as a function of lead shield thickness [4].

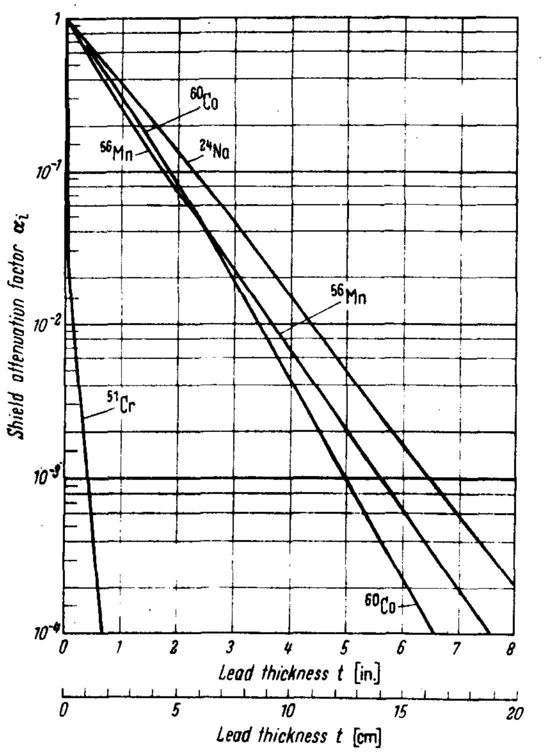

Fig. 9.1.–4. Radiation dose rate shield attenuation factor for ^{24}Na, ^{51}Cr, ^{56}Mn and ^{60}Co as a function of lead shield thickness [4].

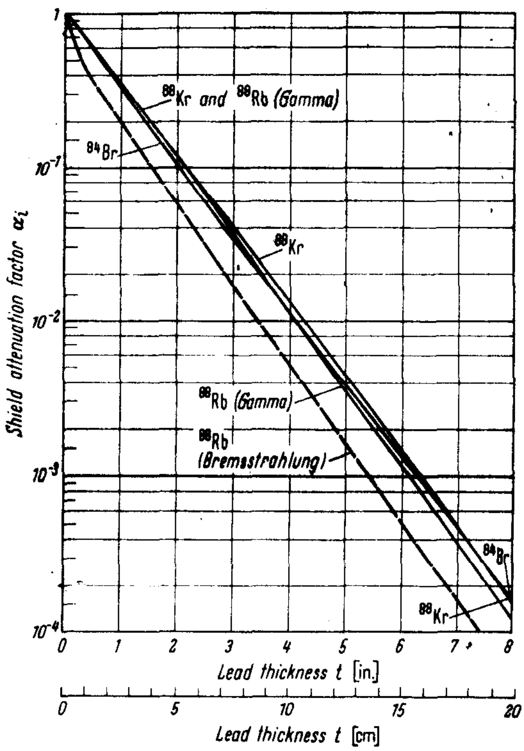

Fig. 9.1.–6. Radiation dose rate shield attenuation factor for ^{84}Br, ^{88}Kr and ^{88}Rb as a function of lead shield thickness [4].

Note: The curve for ^{88}Kr–^{88}Rb (gamma) falls between the individual curves for ^{88}Kr and 88Rb (gamma). In the interest of clarity, the curve for the combined isotopes is not shown.

Table 9.1.-3. Exposure attenuation factors I/I_0 for broad beam gamma radiation of a point isotropic source in *lead* ($\varrho = 11\,340$ kg/m^3) in dependence on the energy of incident gamma radiation E_0 [3]

Note: Attenuation factor .3480 09– read: $0.3480 \cdot 10^{-9}$

r [cm]	E_0 [MeV] 0.5	0.6	0.8	1.0	1.25	1.5	2.0	2.5	3.0	3.5	4.0	4.5
0.1	.8820 00	.9105 00	.9383 00	.9516 00	.9596 00	.9633 00	.9666 00	.9676 00	.9669 00	.9657 00	.9646 00	.9632 00
0.2	.7757 00	.8274 00	.8792 00	.9047 00	.9202 00	.9276 00	.9341 00	.9361 00	.9347 00	.9324 00	.9304 00	.9277 00
0.3	.6806 00	.7504 00	.8229 00	.8594 00	.8819 00	.8927 00	.9024 00	.9053 00	.9035 00	.9002 00	.8973 00	.8935 00
0.4	.5958 00	.6795 00	.7693 00	.8156 00	.8447 00	.8588 00	.8715 00	.8754 00	.8732 00	.8690 00	.8654 00	.8604 00
0.5	.5206 00	.6143 00	.7184 00	.7733 00	.8086 00	.8259 00	.8414 00	.8462 00	.8438 00	.8388 00	.8345 00	.8286 00
0.6	.4540 00	.5545 00	.6701 00	.7328 00	.7737 00	.7939 00	.8122 00	.8179 00	.8152 00	.8096 00	.8046 00	.7979 00
0.7	.3953 00	.4999 00	.6246 00	.6938 00	.7399 00	.7628 00	.7837 00	.7903 00	.7875 00	.7813 00	.7758 00	.7683 00
0.8	.3437 00	.4502 00	.5816 00	.6564 00	.7072 00	.7327 00	.7561 00	.7635 00	.7607 00	.7539 00	.7479 00	.7397 00
0.9	.2984 00	.4049 00	.5411 00	.6207 00	.6757 00	.7035 00	.7292 00	.7375 00	.7346 00	.7274 00	.7210 00	.7122 00
1.0	.2588 00	.3638 00	.5030 00	.5865 00	.6453 00	.6752 00	.7031 00	.7123 00	.7093 00	.7017 00	.6950 00	.6857 00
1.2	.1940 00	.2989 00	.4338 00	.5228 00	.5878 00	.6215 00	.6532 00	.6639 00	.6611 00	.6529 00	.6457 00	.6355 00
1.4	.1448 00	.2350 00	.3731 00	.4650 00	.5346 00	.5713 00	.6063 00	.6184 00	.6159 00	.6073 00	.5997 00	.5889 00
1.6	.1078 00	.1880 00	.3201 00	.4128 00	.4856 00	.5246 00	.5623 00	.5757 00	.5735 00	.5646 00	.5568 00	.5456 00
1.8	.8005 01–	.1500 00	.2741 00	.3658 00	.4404 00	.4812 00	.5211 00	.5356 00	.5337 00	.5248 00	.5168 00	.5054 00
2.0	.5925 01–	.1194 00	.2343 00	.3236 00	.3990 00	.4409 00	.4826 00	.4979 00	.4965 00	.4876 00	.4797 00	.4681 00
2.2	.4378 01–	.9492 01–	.1999 00	.2859 00	.3611 00	.4037 00	.4465 00	.4627 00	.4617 00	.4529 00	.4450 00	.4334 00
2.4	.3229 01–	.7528 01–	.1702 00	.2522 00	.3264 00	.3592 00	.4129 00	.4297 00	.4292 00	.4206 00	.4128 00	.4013 00
2.6	.2378 01–	.5961 01–	.1448 00	.2222 00	.2948 00	.3374 00	.3816 00	.3989 00	.3988 00	.3904 00	.3829 00	.3715 00
2.8	.1748 01–	.4713 01–	.1230 00	.1956 00	.2659 00	.3082 00	.3525 00	.3700 00	.3704 00	.3623 00	.3550 00	.3439 00
3.0	.1284 01–	.3722 01–	.1043 00	.1719 00	.2397 00	.2812 00	.3253 00	.3432 00	.3439 00	.3361 00	.3291 00	.3183 00
3.5	.5913 02–	.2052 01–	.6888 01–	.1240 00	.1843 00	.2231 00	.2657 00	.2836 00	.2853 00	.2784 00	.2721 00	.2621 00
4.0	.2708 02–	.1125 01–	.4519 01–	.8905 01–	.1411 00	.1763 00	.2164 00	.2339 00	.2362 00	.2302 00	.2247 00	.2157 00
4.5	.1236 02–	.6144 02–	.2951 01–	.6363 01–	.1076 00	.1388 00	.1757 00	.1924 00	.1952 00	.1901 00	.1854 00	.1774 00
5.0	.5625 03–	.3342 02–	.1919 01–	.4529 01–	.8186 01–	.1090 00	.1423 00	.1580 00	.1611 00	.1568 00	.1528 00	.1458 00
5.5	.2554 03–	.1812 02–	.1244 01–	.3213 01–	.6205 01–	.8544 01–	.1151 00	.1294 00	.1327 00	.1291 00	.1258 00	.1197 00
6.0	.1158 03–	.9808 03–	.8044 02–	.2273 01–	.4692 01–	.6677 01–	.9287 01–	.1059 00	.1092 00	.1062 00	.1035 00	.9850 01–
6.5	.5247 04–	.5297 03–	.5187 02–	.1604 01–	.3539 01–	.5207 01–	.7480 01–	.8654 01–	.8980 01–	.8738 01–	.8510 01–	.8064 01–
7.0	.2374 04–	.2856 03–	.3337 02–	.1129 01–	.2664 01–	.4054 01–	.6015 01–	.7059 01–	.7372 01–	.7176 01–	.6991 01–	.6612 01–
7.5	.1073 04–	.1538 03–	.2143 02–	.7936 02–	.2002 01–	.3150 01–	.4829 01–	.5751 01–	.6045 01–	.5889 01–	.5740 01–	.5419 01–
8.0	.4854 05–	.8278 04–	.1374 02–	.5567 02–	.1502 01–	.2444 01–	.3872 01–	.4680 01–	.4953 01–	.4828 01–	.4709 01–	.4440 01–
8.5	.2193 05–	.4450 04–	.8804 03–	.3899 02–	.1125 01–	.1894 01–	.3101 01–	.3804 01–	.4054 01–	.3956 01–	.3861 01–	.3635 01–
9.0	.9907 06–	.2390 04–	.5631 03–	.2727 02–	.8420 02–	.1466 01–	.2481 01–	.3089 01–	.3316 01–	.3239 01–	.3164 01–	.2976 01–
9.5	.4474 06–	.1283 04–	.3598 03–	.1905 02–	.6292 02–	.1133 01–	.1982 01–	.2506 01–	.2710 01–	.2650 01–	.2592 01–	.2435 01–
10.0	.2020 06–	.6889 05–	.2297 03–	.1329 02–	.4696 02–	.8750 02–	.1582 01–	.2031 01–	.2213 01–	.2167 01–	.2122 01–	.1992 01–
11.0	.4121 07–	.1982 05–	.9342 04–	.6457 03–	.2608 02–	.5202 02–	.1006 01–	.1331 01–	.1472 01–	.1446 01–	.1420 01–	.1331 01–
12.0	.8392 08–	.5697 06–	.3789 04–	.3126 03–	.1443 02–	.3082 02–	.6375 02–	.8703 02–	.9779 02–	.9639 02–	.9493 02–	.8890 02–
13.0	.1709 08–	.1636 06–	.1534 04–	.1509 03–	.7970 03–	.1821 02–	.4028 02–	.5674 02–	.6479 02–	.6410 02–	.6335 02–	.5929 02–
14.0	.3480 09–	.4708 07–	.6205 05–	.7271 04–	.4388 03–	.1073 02–	.2540 02–	.3691 02–	.4284 02–	.4256 02–	.4222 02–	.3950 02–
15.0		.1350 07–	.2505 05–	.3497 04–	.2411 03–	.6312 03–	.1598 02–	.2397 02–	.2828 02–	.2822 02–	.2810 02–	.2630 02–
16.0		.3872 08–	.1010 05–	.1679 04–	.1322 03–	.3705 03–	.1003 02–	.1553 02–	.1864 02–	.1868 02–	.1869 02–	.1750 02–
17.0		.1110 08–	.4074 06–	.8055 05–	.7244 04–	.2171 03–	.6292 03–	.1005 02–	.1227 02–	.1236 02–	.1242 02–	.1163 02–
18.0		.3184 09–	.1641 06–	.3860 05–	.3962 04–	.1270 03–	.3939 03–	.6499 03–	.8072 03–	.8167 03–	.8245 03–	.7731 03–
19.0			.6612 07–	.1848 05–	.2164 04–	.7488 04–	.2463 03–	.4195 03–	.5302 03–	.5392 03–	.5469 03–	.5134 03–
20.0			.2675 07–	.8842 06–	.1181 04–	.4357 04–	.1538 03–	.2705 03–	.3479 03–	.3556 03–	.3626 03–	.3407 03–
21.0			.1075 07–	.4228 06–	.6442 05–	.2529 04–	.9598 04–	.1743 03–	.2281 03–	.2344 03–	.2402 03–	.2261 03–
22.0			.4325 08–	.2020 06–	.3510 05–	.1474 04–	.5983 04–	.1121 03–	.1494 03–	.1544 03–	.1590 03–	.1499 03–
23.0			.1739 08–	.9654 07–	.1911 05–	.8586 05–	.3726 04–	.7215 04–	.9784 04–	.1016 03–	.1052 03–	.9942 04–
24.0			.6994 09–	.4610 07–	.1040 05–	.4996 05–	.2319 04–	.4637 04–	.6401 04–	.6688 04–	.6965 04–	.6589 04–
25.0			.2812 09–	.2201 07–	.5660 06–	.2906 05–	.1442 04–	.2978 04–	.4185 04–	.4398 04–	.4606 04–	.4366 04–
26.0				.1057 07–	.3077 06–	.1689 05–	.8967 05–	.1911 04–	.2735 04–	.2890 04–	.3044 04–	.2892 04–
27.0				.5042 08–	.1673 06–	.9815 06–	.5570 05–	.1226 04–	.1786 04–	.1899 04–	.2012 04–	.1915 04–
28.0				.2404 08–	.9090 07–	.5700 06–	.3459 05–	.7864 05–	.1166 04–	.1247 04–	.1329 04–	.1268 04–
29.0				.1146 08–	.4938 07–	.3309 06–	.2147 05–	.5040 05–	.7614 05–	.8189 05–	.8779 05–	.8394 05–
30.0				.5463 09–	.2681 07–	.1920 06–	.1332 05–	.3229 05–	.4967 05–	.5375 05–	.5796 05–	.5555 05–
31.0				.2604 09–	.1473 07–	.1114 06–	.8261 06–	.2068 05–	.3240 05–	.3527 05–	.3826 05–	.3676 05–
32.0					.7985 08–	.6464 07–	.5122 06–	.1324 05–	.2112 05–	.2313 05–	.2525 05–	.2432 05–
33.0					.4328 08–	.3748 07–	.3174 06–	.8474 06–	.1376 05–	.1517 05–	.1666 05–	.1609 05–
34.0					.2346 08–	.2173 07–	.1967 06–	.5422 06–	.8972 06–	.9949 06–	.1099 05–	.1064 05–
35.0					.1272 08–	.1259 07–	.1218 06–	.3468 06–	.5845 06–	.6522 06–	.7252 06–	.7041 06–
36.0					.6896 09–	.7396 08–	.7547 07–	.2218 06–	.3807 06–	.4275 06–	.4783 06–	.4656 06–
37.0					.3738 09–	.4280 08–	.4673 07–	.1418 06–	.2479 06–	.2801 06–	.3154 06–	.3079 06–
38.0					.2026 09–	.2477 08–	.2893 07–	.9068 07–	.1614 06–	.1835 06–	.2079 06–	.2036 06–
39.0						.1433 08–	.1791 07–	.5795 07–	.1051 06–	.1202 06–	.1371 06–	.1346 06–
40.0						.8296 09–	.1108 07–	.3703 07–	.6841 07–	.7877 07–	.9039 07–	.8901 07–
41.0						.4801 09–	.6966 08–	.2366 07–	.4452 07–	.5159 07–	.5958 07–	.5884 07–
42.0						.2778 09–	.4304 08–	.1512 07–	.2897 07–	.3379 07–	.3927 07–	.3890 07–
43.0							.2659 08–	.9812 08–	.1885 07–	.2212 07–	.2588 07–	.2584 07–
44.0							.1643 08–	.6259 08–	.1226 07–	.1465 07–	.1719 07–	.1707 07–
45.0							.1015 08–	.3992 08–	.8081 08–	.9583 08–	.1132 07–	.1128 07–
46.0							.6275 09–	.2546 08–	.5251 08–	.6268 08–	.7457 08–	.7454 08–
47.0							.3877 09–	.1684 08–	.3412 08–	.4100 08–	.4910 08–	.4984 08–
48.0							.2395 09–	.1036 08–	.2217 08–	.2682 08–	.3234 08–	.3253 08–
49.0								.6611 09–	.1440 08–	.1754 08–	.2129 08–	.2149 08–
50.0								.4217 09–	.9562 09–	.1147 08–	.1402 08–	.1420 08–

Table 9.1.-3. (Continued)

E_0 [MeV] 5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	r [cm]
.9617 00	.9607 00	.9596 00	.9584 00	.9573 00	.9561 00	.9549 00	.9536 00	.9523 00	.9509 00	.9496 00	0.1
.9250 00	.9229 00	.9208 00	.9185 00	.9165 00	.9141 00	.9120 00	.9094 00	.9070 00	.9044 00	.9018 00	0.2
.8896 00	.8866 00	.8836 00	.8803 00	.8774 00	.8741 00	.8710 00	.8673 00	.8639 00	.8602 00	.8565 00	0.3
.8556 00	.8517 00	.8479 00	.8438 00	.8400 00	.8358 00	.8319 00	.8272 00	.8228 00	.8182 00	.8135 00	0.4
.8228 00	.8182 00	.8136 00	.8087 00	.8043 00	.7992 00	.7946 00	.7890 00	.7838 00	.7783 00	.7727 00	0.5
.7913 00	.7860 00	.7808 00	.7751 00	.7701 00	.7643 00	.7589 00	.7526 00	.7467 00	.7403 00	.7340 00	0.6
.7610 00	.7551 00	.7493 00	.7430 00	.7373 00	.7309 00	.7250 00	.7179 00	.7113 00	.7043 00	.6973 00	0.7
.7318 00	.7254 00	.7190 00	.7122 00	.7060 00	.6990 00	.6925 00	.6848 00	.6777 00	.6701 00	.6625 00	0.8
.7037 00	.6968 00	.6900 00	.6826 00	.6760 00	.6685 00	.6616 00	.6533 00	.6457 00	.6375 00	.6294 00	0.9
.6767 00	.6694 00	.6621 00	.6543 00	.6473 00	.6394 00	.6320 00	.6233 00	.6152 00	.6066 00	.5981 00	1.0
.6257 00	.6176 00	.6097 00	.6012 00	.5936 00	.5849 00	.5769 00	.5674 00	.5586 00	.5493 00	.5401 00	1.2
.5785 00	.5699 00	.5615 00	.5525 00	.5444 00	.5351 00	.5267 00	.5166 00	.5074 00	.4976 00	.4878 00	1.4
.5348 00	.5258 00	.5171 00	.5077 00	.4993 00	.4897 00	.4809 00	.4705 00	.4609 00	.4508 00	.4407 00	1.6
.4943 00	.4852 00	.4762 00	.4666 00	.4580 00	.4481 00	.4392 00	.4285 00	.4188 00	.4085 00	.3983 00	1.8
.4569 00	.4476 00	.4386 00	.4289 00	.4201 00	.4102 00	.4012 00	.3904 00	.3806 00	.3702 00	.3600 00	2.0
.4223 00	.4130 00	.4039 00	.3942 00	.3854 00	.3755 00	.3665 00	.3557 00	.3459 00	.3357 00	.3255 00	2.2
.3903 00	.3810 00	.3720 00	.3623 00	.3536 00	.3437 00	.3348 00	.3242 00	.3145 00	.3044 00	.2944 00	2.4
.3607 00	.3515 00	.3426 00	.3331 00	.3245 00	.3147 00	.3060 00	.2955 00	.2860 00	.2761 00	.2663 00	2.6
.3333 00	.3243 00	.3156 00	.3062 00	.2978 00	.2882 00	.2796 00	.2694 00	.2601 00	.2505 00	.2410 00	2.8
.3079 00	.2991 00	.2907 00	.2815 00	.2733 00	.2640 00	.2556 00	.2456 00	.2367 00	.2273 00	.2181 00	3.0
.2526 00	.2445 00	.2366 00	.2382 00	.2206 00	.2120 00	.2043 00	.1952 00	.1870 00	.1785 00	.1702 00	3.5
.2072 00	.1997 00	.1927 00	.1850 00	.1782 00	.1704 00	.1635 00	.1552 00	.1479 00	.1403 00	.1330 00	4.0
.1699 00	.1632 00	.1569 00	.1501 00	.1440 00	.1370 00	.1309 00	.1236 00	.1171 00	.1105 00	.1041 00	4.5
.1392 00	.1333 00	.1278 00	.1218 00	.1164 00	.1102 00	.1049 00	.9853 01-	.9289 01-	.8713 01-	.8160 01-	5.0
.1140 00	.1089 00	.1041 00	.9887 01-	.9416 01-	.8880 01-	.8417 01-	.7860 01-	.7373 01-	.6878 01-	.6405 01-	5.5
.9343 01-	.8893 01-	.8479 01-	.8027 01-	.7619 01-	.7155 01-	.6756 01-	.6276 01-	.5858 01-	.5436 01-	.5034 01-	6.0
.7650 01-	.7262 01-	.6907 01-	.6518 01-	.6168 01-	.5768 01-	.5426 01-	.5016 01-	.4659 01-	.4301 01-	.3961 01-	6.5
.6262 01-	.5929 01-	.5627 01-	.5294 01-	.4995 01-	.4652 01-	.4361 01-	.4012 01-	.3709 01-	.3407 01-	.3121 01-	7.0
.5125 01-	.4840 01-	.4584 01-	.4301 01-	.4046 01-	.3754 01-	.3508 01-	.3211 01-	.2956 01-	.2701 01-	.2462 01-	7.5
.4193 01-	.3951 01-	.3734 01-	.3495 01-	.3279 01-	.3031 01-	.2823 01-	.2572 01-	.2357 01-	.2144 01-	.1945 01-	8.0
.3430 01-	.3225 01-	.3043 01-	.2841 01-	.2658 01-	.2448 01-	.2273 01-	.2062 01-	.1882 01-	.1704 01-	.1538 01-	8.5
.2805 01-	.2632 01-	.2479 01-	.2309 01-	.2155 01-	.1978 01-	.1832 01-	.1654 01-	.1503 01-	.1355 01-	.1217 01-	9.0
.2293 01-	.2148 01-	.2020 01-	.1877 01-	.1748 01-	.1599 01-	.1476 01-	.1328 01-	.1202 01-	.1078 01-	.9649 02-	9.5
.1875 01-	.1752 01-	.1646 01-	.1527 01-	.1418 01-	.1293 01-	.1191 01-	.1066 01-	.9618 02-	.8593 02-	.7653 02-	10.0
.1252 01-	.1166 01-	.1093 01-	.1010 01-	.9348 02-	.8468 02-	.7760 02-	.6894 02-	.6169 02-	.5467 02-	.4827 02-	11.0
.8362 02-	.7766 02-	.7262 02-	.6689 02-	.6165 02-	.5551 02-	.5064 02-	.4464 02-	.3966 02-	.3487 02-	.3055 02-	12.0
.5579 02-	.5167 02-	.4824 02-	.4431 02-	.4069 02-	.3643 02-	.3309 02-	.2896 02-	.2556 02-	.2230 02-	.1939 02-	13.0
.3720 02-	.3437 02-	.3203 02-	.2936 02-	.2687 02-	.2394 02-	.2166 02-	.1882 02-	.1650 02-	.1429 02-	.1233 02-	14.0
.2479 02-	.2286 02-	.2129 02-	.1946 02-	.1776 02-	.1574 02-	.1419 02-	.1225 02-	.1067 02-	.9182 03-	.7868 03-	15.0
.1652 02-	.1520 02-	.1415 02-	.1291 02-	.1175 02-	.1036 02-	.9309 03-	.7984 03-	.6911 03-	.5907 03-	.5027 03-	16.0
.1100 02-	.1010 02-	.9406 03-	.8567 03-	.7776 03-	.6824 03-	.6111 03-	.5209 03-	.4482 03-	.3805 03-	.3217 03-	17.0
.7327 03-	.6719 03-	.6251 03-	.5685 03-	.5148 03-	.4497 03-	.4015 03-	.3401 03-	.2910 03-	.2455 03-	.2062 03-	18.0
.4877 03-	.4466 03-	.4155 03-	.3774 03-	.3409 03-	.2965 03-	.2640 03-	.2223 03-	.1891 03-	.1585 03-	.1323 03-	19.0
.3245 03-	.2968 03-	.2762 03-	.2505 03-	.2259 03-	.1956 03-	.1737 03-	.1454 03-	.1230 03-	.1025 03-	.8505 04-	20.0
.2159 03-	.1972 03-	.1836 03-	.1664 03-	.1497 03-	.1291 03-	.1143 03-	.9519 04-	.8007 04-	.6632 04-	.5470 04-	21.0
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.4222 04-	.3844 04-	.3587 04-	.3242 04-	.2896 04-	.2459 04-	.2157 04-	.1756 04-	.1445 04-	.1169 04-	.9424 05-	25.0
.2806 04-	.2553 04-	.2385 04-	.2154 04-	.1921 04-	.1625 04-	.1422 04-	.1151 04-	.9434 05-	.7590 05-	.6079 05-	26.0
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.1239 04-	.1126 04-	.1054 04-	.9519 05-	.8463 05-	.7106 05-	.6193 05-	.4961 05-	.4020 05-	.3198 05-	.2532 05-	28.0
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.2415 05-	.2192 05-	.2061 05-	.1859 05-	.1643 05-	.1360 05-	.1176 05-	.9284 06-	.7322 06-	.5693 06-	.4408 06-	32.0
.1604 05-	.1456 05-	.1371 05-	.1236 05-	.1091 05-	.9000 06-	.7766 06-	.6059 06-	.4785 06-	.3700 06-	.2849 06-	33.0
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.7079 06-	.6422 06-	.6063 06-	.5467 06-	.4813 06-	.3940 06-	.3387 06-	.2615 06-	.2044 06-	.1563 06-	.1190 06-	35.0
.4702 06-	.4264 06-	.4032 06-	.3635 06-	.3196 06-	.2607 06-	.2237 06-	.1718 06-	.1336 06-	.1015 06-	.7698 07-	36.0
.3123 06-	.2832 06-	.2679 06-	.2417 06-	.2123 06-	.1725 06-	.1477 06-	.1129 06-	.8736 07-	.6588 07-	.4961 07-	37.0
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.2297 08-	.2081 08-	.2006 08-	.1810 08-	.1565 08-	.1220 08-	.1021 08-	.7333 09-	.5336 09-	.3771 09-	.2655 09-	49.0
.1525 08-	.1382 08-	.1334 08-	.1204 08-	.1040 08-	.8080 09-	.6749 09-	.4821 09-	.3490 09-	.2452 09-	.1717 09-	50.0

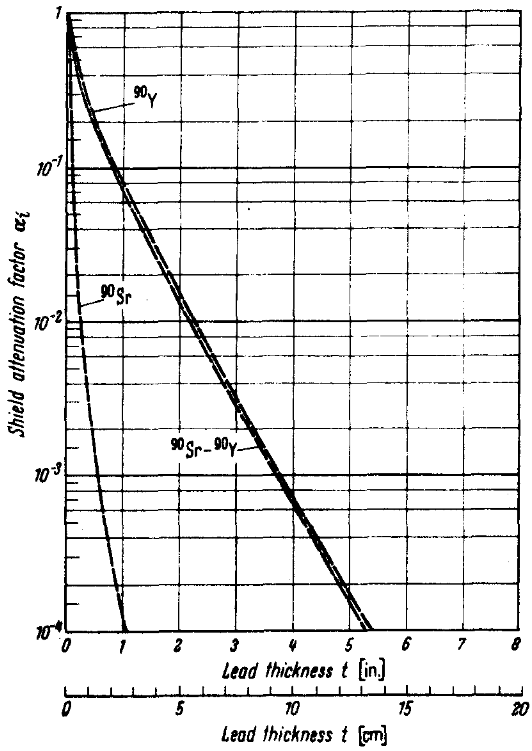

Fig. 9.1.–7. Radiation dose rate shield attenuation factor for ^{90}Sr, $^{90}Sr-^{90}Y$ and ^{90}Y as function of lead shield thickness [4].

Note: All curves are for bremsstrahlung.

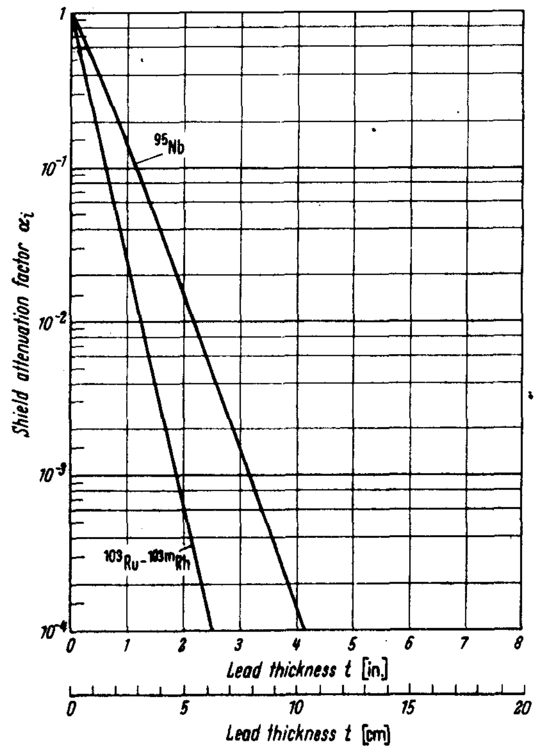

Fig. 9.1.–9. Radiation dose rate shield attenuation factor for ^{95}Nb and $^{103}Ru-^{103m}Rh$ as a function of lead shield thickness [4].

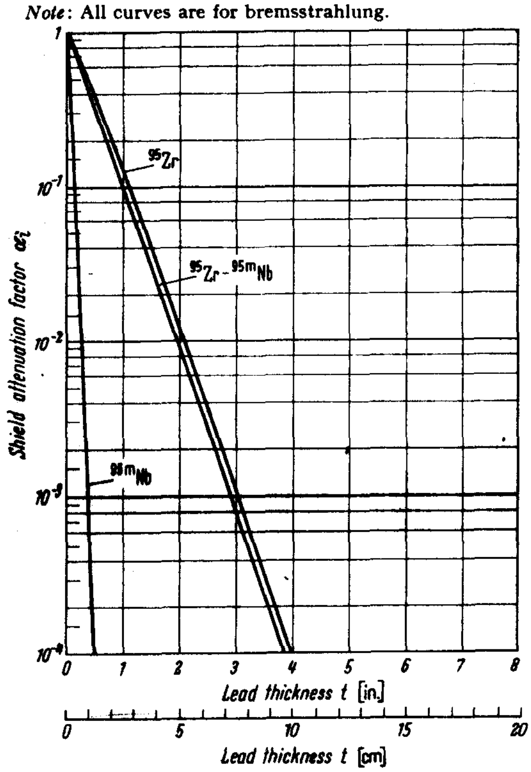

Fig. 9.1.–8. Radiation dose rate shield attenuation factor for ^{95}Zr, $^{95}Zr-^{95m}Nb$ and ^{95m}Nb as a function of lead shield thickness [4].

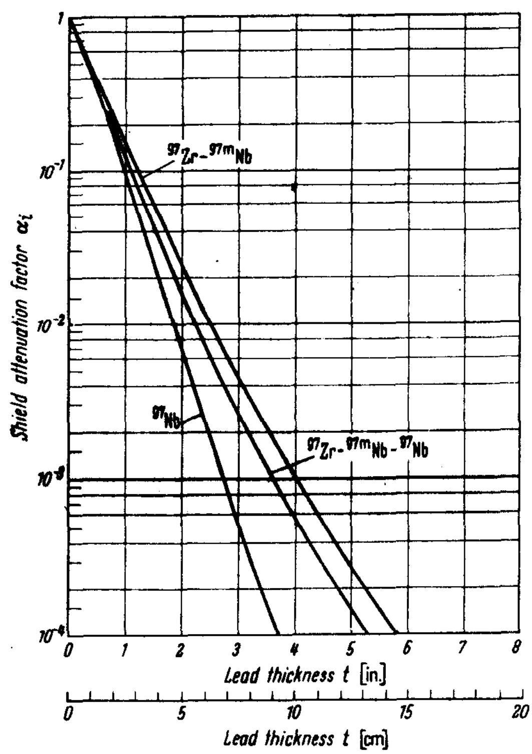

Fig. 9.1.–10. Radiation dose rate shield attenuation factor for ^{97}Nb, $^{97}Zr-^{97m}Nb$ and $^{97}Zr-^{97m}Nb-^{97}Nb$ as a function of lead shield thickness [4].