APPENDIX to the Examination Co-ordinating Radiation Protection Expert

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Nuclear Research and consultancy Group	NRG
Delft University of Technology	TU Delft
Boerhaave CME/LUMC	BN/LUMC
University of Groningen	RUG
Radboudumc	RUMC
Eindhoven University of Technology	TU/e

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examination date:
11 December 2017
duration of examination: 13:30 - 16:30

Instructions:

- ☐ **If you use any data other than the data provided in this appendix, please state the source!**
- ☐ **This appendix consists of 16 numbered pages. Please check whether it is complete!**

TABLE OF CONTENTS

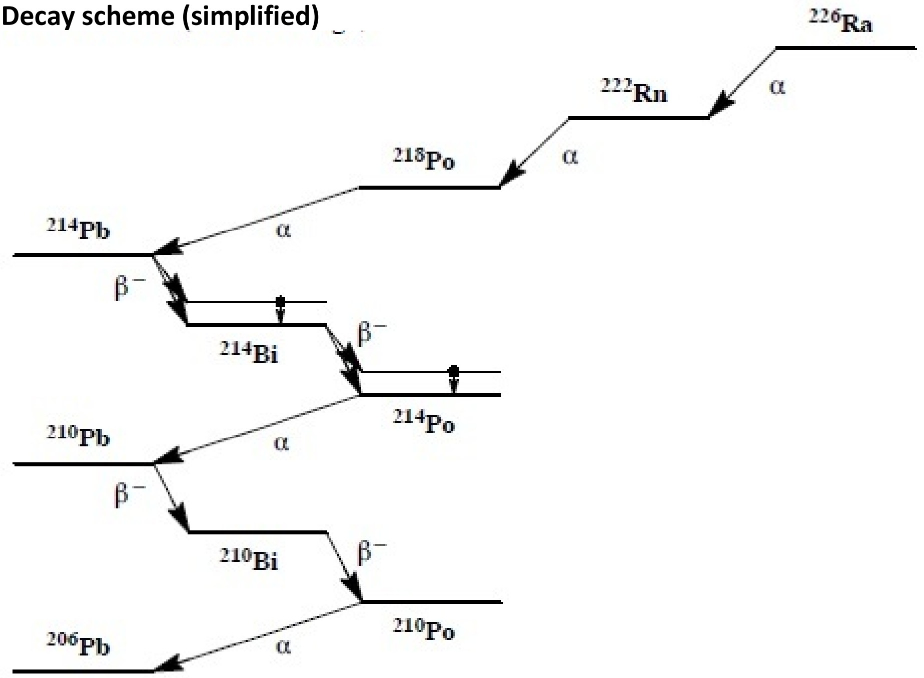
Handboek Radionucliden, [Radionuclides Handbook], A.S. Keverling Buisman (2nd edition 2007), pp. 230-231, ^{226}Ra data

^{226}Ra (+ dochters) Z = 88

Half-life and decay constant

$T_{1/2} = 1{,}60\times10^{3}$ j $= 5{,}05\times10^{10}$ s $\qquad \lambda = 1{,}37\times10^{-11}\ \mathrm{s}^{-1}$

Decay scheme (simplified)



Source constants (including daughter nuclides)

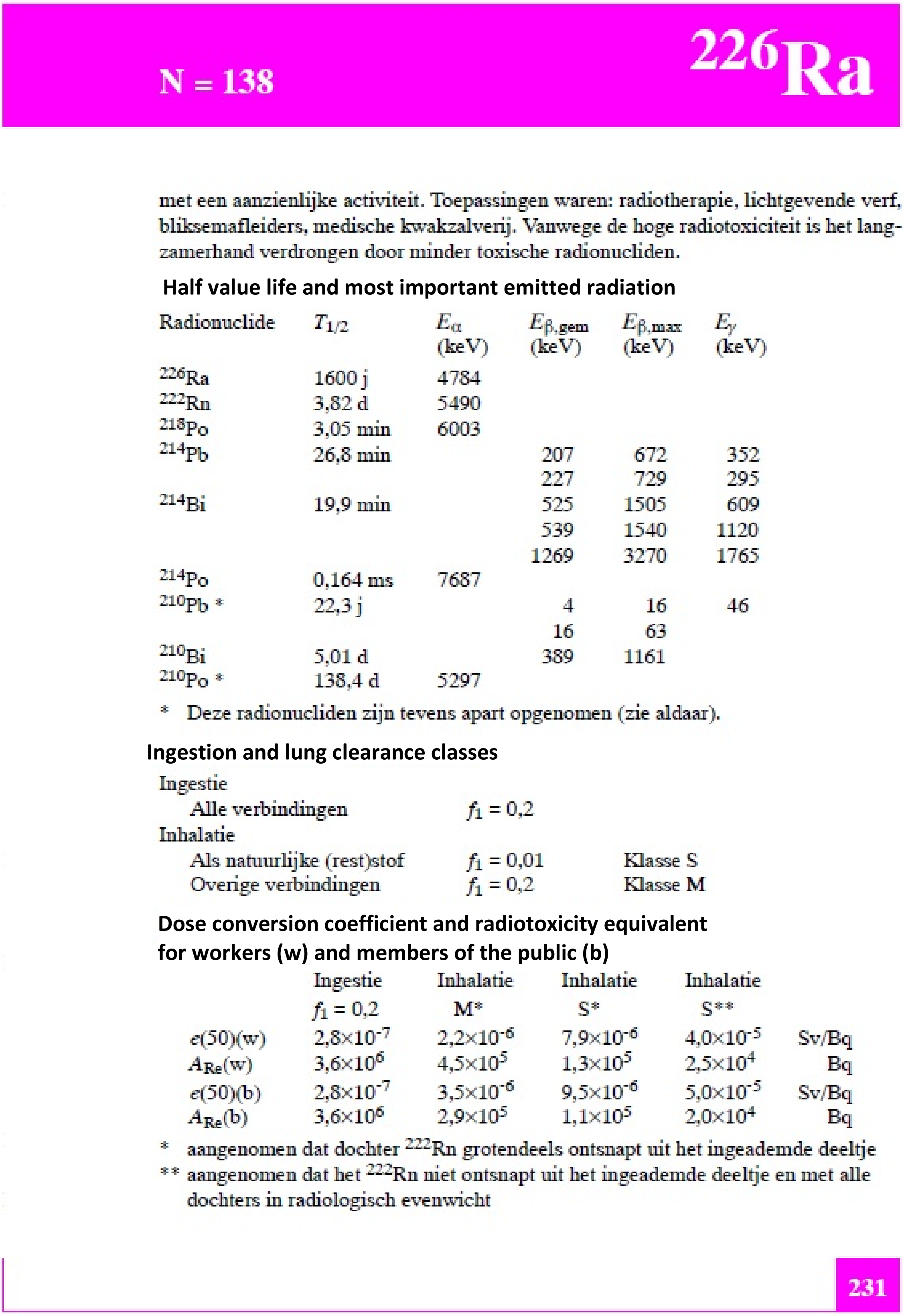
Air kerma rate $k = 0{,}28\ \mu\mathrm{Gy/h\ per\ MBq/m^2}$
Ambient dose equivalent rate $h = 0{,}26\ \mu\mathrm{Sv/h\ per\ MBq/m^2}$

Miscellaneous (including daughter nuclides)

Specific activity (only ^{226}Ra) $A_{sp} = 3{,}7\times10^{10}$ Bq/g (1 g Ra ≡ 1 Ci !)
Exemption levels $C_v = 10^{0} = 1$ Bq/g en $A_v = 10^{4}$ Bq
Skin contamination $H_{huid} = 6\times10^{-10}$ Sv/s per Bq/cm^2
Wound contamination / injection $e(50) = 4{,}3\times10^{-6}$ Sv/Bq
Transport $A_1 = 0{,}2$ TBq en $A_2 = 0{,}003$ TBq

Production and applications

Het radionuclide ^{226}Ra is een natuurproduct. Het komt voor in de uraniumvervalreeks. Er is een reeks van toepassingen geweest, toen het nuclide de enige radioactieve stof was



met een aanzienlijke activiteit. Toepassingen waren: radiotherapie, lichtgevende verf, bliksemafleiders, medische kwakzalverij. Vanwege de hoge radiotoxiciteit is het langzamerhand verdrongen door minder toxische radionucliden.

Half value life and most important emitted radiation

Radionuclide	$T_{1/2}$	E_α (keV)	$E_{\beta,\mathrm{gem}}$ (keV)	$E_{\beta,\mathrm{max}}$ (keV)	E_γ (keV)
^{226}Ra	1600 j	4784			
^{222}Rn	3,82 d	5490			
^{218}Po	3,05 min	6003			
^{214}Pb	26,8 min		207	672	352
			227	729	295
^{214}Bi	19,9 min		525	1505	609
			539	1540	1120
			1269	3270	1765
^{214}Po	0,164 ms	7687			
^{210}Pb *	22,3 j		4	16	46
			16	63	
^{210}Bi	5,01 d		389	1161	
^{210}Po *	138,4 d	5297			

* Deze radionucliden zijn tevens apart opgenomen (zie aldaar).

Ingestion and lung clearance classes

Ingestie		
Alle verbindingen	$f_1 = 0{,}2$	
Inhalatie		
Als natuurlijke (rest)stof	$f_1 = 0{,}01$	Klasse S
Overige verbindingen	$f_1 = 0{,}2$	Klasse M

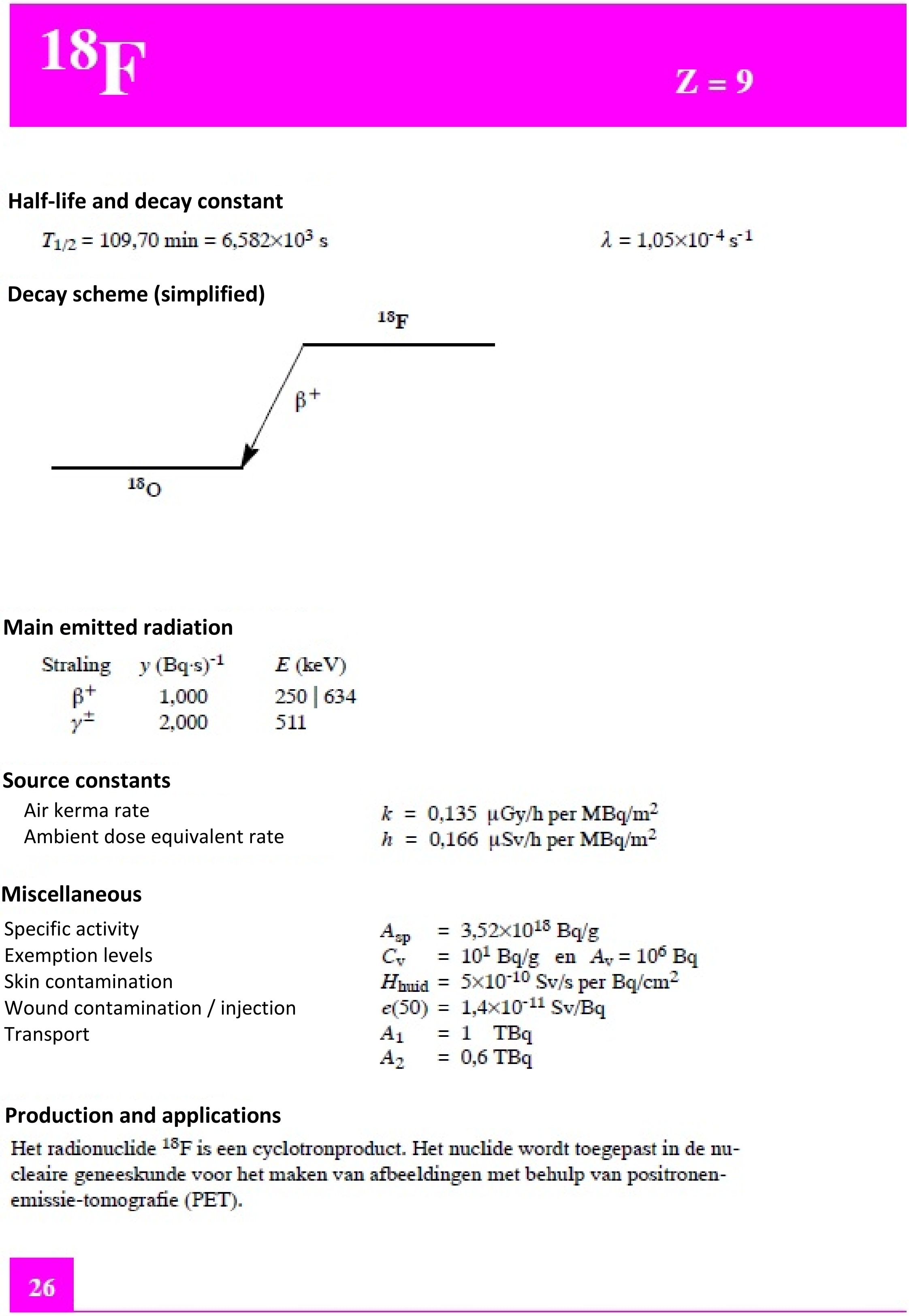
Dose conversion coefficient and radiotoxicity equivalent for workers (w) and members of the public (b)

	Ingestie $f_1 = 0{,}2$	Inhalatie M*	Inhalatie S*	Inhalatie S**	
$e(50)(\mathrm{w})$	$2{,}8\times10^{-7}$	$2{,}2\times10^{-6}$	$7{,}9\times10^{-6}$	$4{,}0\times10^{-5}$	Sv/Bq
$A_{\mathrm{Re}}(\mathrm{w})$	$3{,}6\times10^{6}$	$4{,}5\times10^{5}$	$1{,}3\times10^{5}$	$2{,}5\times10^{4}$	Bq
$e(50)(\mathrm{b})$	$2{,}8\times10^{-7}$	$3{,}5\times10^{-6}$	$9{,}5\times10^{-6}$	$5{,}0\times10^{-5}$	Sv/Bq
$A_{\mathrm{Re}}(\mathrm{b})$	$3{,}6\times10^{6}$	$2{,}9\times10^{5}$	$1{,}1\times10^{5}$	$2{,}0\times10^{4}$	Bq

* aangenomen dat dochter ^{222}Rn grotendeels ontsnapt uit het ingeademde deeltje

** aangenomen dat het ^{222}Rn niet ontsnapt uit het ingeademde deeltje en met alle dochters in radiologisch evenwicht

Handboek Radionucliden, [Radionuclides Handbook], A.S. Keverling Buisman (2nd edition 2007), p 26, ^{18}F data.



^{18}F

$Z = 9$

Half-life and decay constant

$T_{1/2} = 109{,}70$ min $= 6{,}582\times10^3$ s

$\lambda = 1{,}05\times10^{-4}$ s^{-1}

Decay scheme (simplified)

Main emitted radiation

Straling	y (Bq·s)$^{-1}$	E (keV)
β^+	1,000	250 | 634
$\gamma^\pm$	2,000	511

Source constants

Air kerma rate	k = 0,135 µGy/h per MBq/m^2
Ambient dose equivalent rate	h = 0,166 µSv/h per MBq/m^2

Miscellaneous

Specific activity	A_{sp} = $3{,}52\times10^{18}$ Bq/g
Exemption levels	C_v = 10^1 Bq/g en $A_v = 10^6$ Bq
Skin contamination	H_{huid} = 5×10^{-10} Sv/s per Bq/cm^2
Wound contamination / injection	$e(50)$ = $1{,}4\times10^{-11}$ Sv/Bq
Transport	A_1 = 1 TBq A_2 = 0,6 TBq

Production and applications

Het radionuclide ^{18}F is een cyclotronproduct. Het nuclide wordt toegepast in de nucleaire geneeskunde voor het maken van afbeeldingen met behulp van positronen-emissie-tomografie (PET).

26

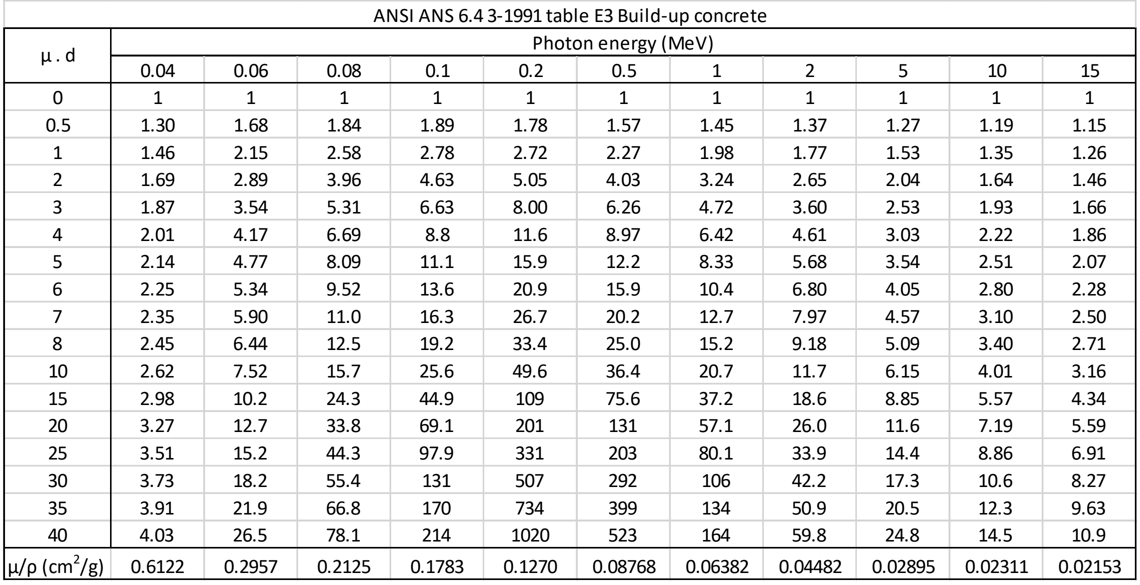
Metabolic model

NIST Standard Reference Database 126: Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption.

	Concrete ρ = 2,35 g/cm^3	
Energy MeV	**μ/ρ** (cm^2/g)	**μ_{en}/ρ** (cm^2/g)
0.01	20.45	19.37
0.015	6.351	5.855
0.02	2.806	2.462
0.03	0.9601	0.7157
0.04	0.5058	0.2995
0.05	0.3412	0.1563
0.06	0.266	0.09554
0.08	0.2014	0.0505
0.1	0.1738	0.03649
0.15	0.1436	0.02897
0.2	0.1282	0.02868
0.3	0.1097	0.02969
0.4	0.09783	0.03024
0.5	0.08915	0.03033
0.6	0.08236	0.03015
0.8	0.07227	0.0294
1	0.06495	0.02843
1.25	0.05807	0.02716
1.5	0.05288	0.02595
2	0.04557	0.02395
3	0.03701	0.0212
4	0.03217	0.01951
5	0.02908	0.0184
6	0.02697	0.01763
8	0.02432	0.01669
10	0.02278	0.01617
15	0.02096	0.01559
20	0.0203	0.01539

Mass attenuation and energy absorption coefficients in concrete in cm^2 g^{-1}.
Concrete density: 2.35 g / cm^3.
http://physics.nist.gov/PhysRefData/XrayMassCoef/ComTab/concrete.html

ANS 6.4.3, D.K. Trubey (September 1988), appendix II table 3, Exposure build-up factors for concrete, page 44.

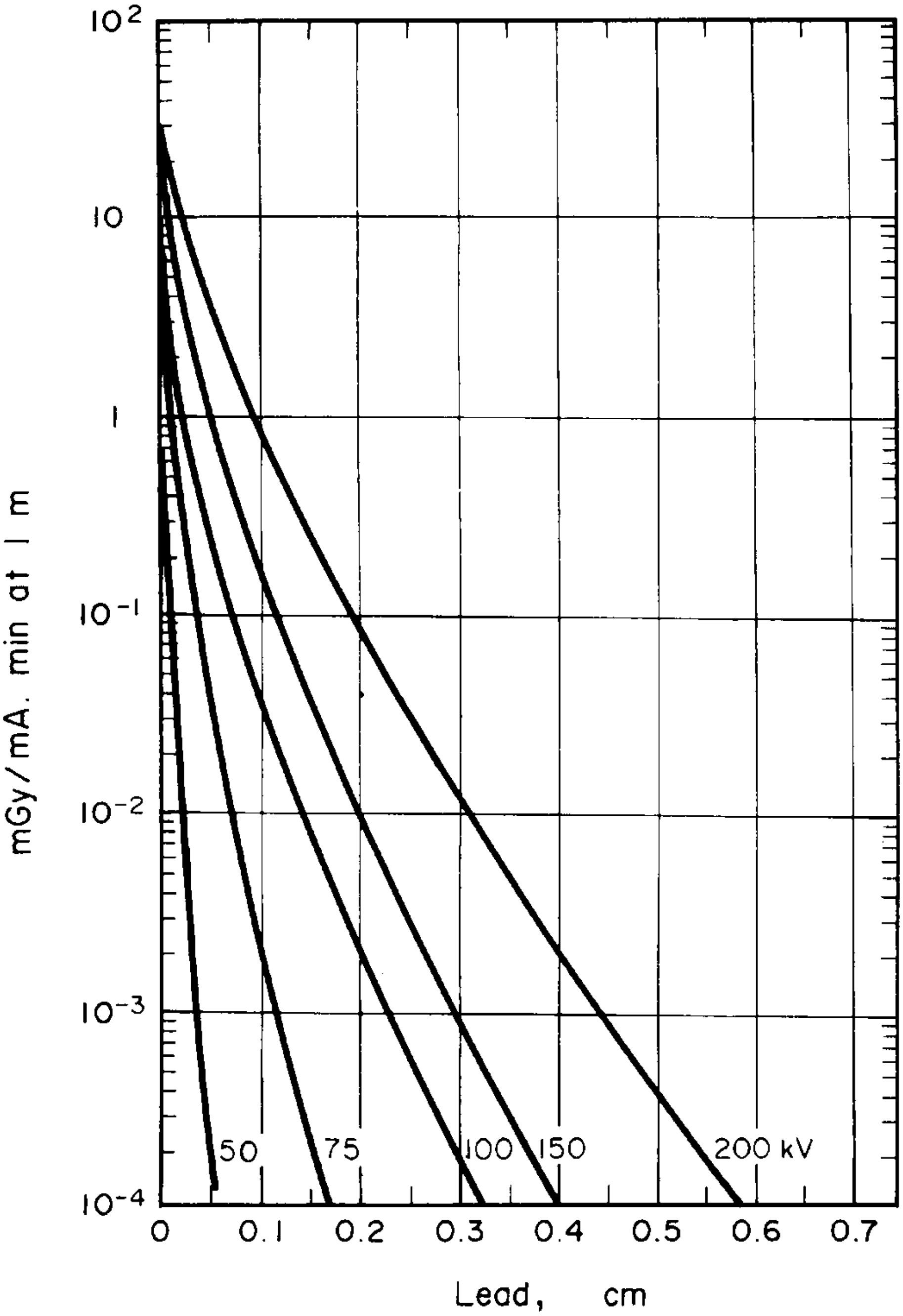


ANSI ANS 6.4 3-1991 table E3 Build-up concrete

μ . d	Photon energy (MeV)										
	0.04	0.06	0.08	0.1	0.2	0.5	1	2	5	10	15
0	1	1	1	1	1	1	1	1	1	1	1
0.5	1.30	1.68	1.84	1.89	1.78	1.57	1.45	1.37	1.27	1.19	1.15
1	1.46	2.15	2.58	2.78	2.72	2.27	1.98	1.77	1.53	1.35	1.26
2	1.69	2.89	3.96	4.63	5.05	4.03	3.24	2.65	2.04	1.64	1.46
3	1.87	3.54	5.31	6.63	8.00	6.26	4.72	3.60	2.53	1.93	1.66
4	2.01	4.17	6.69	8.8	11.6	8.97	6.42	4.61	3.03	2.22	1.86
5	2.14	4.77	8.09	11.1	15.9	12.2	8.33	5.68	3.54	2.51	2.07
6	2.25	5.34	9.52	13.6	20.9	15.9	10.4	6.80	4.05	2.80	2.28
7	2.35	5.90	11.0	16.3	26.7	20.2	12.7	7.97	4.57	3.10	2.50
8	2.45	6.44	12.5	19.2	33.4	25.0	15.2	9.18	5.09	3.40	2.71
10	2.62	7.52	15.7	25.6	49.6	36.4	20.7	11.7	6.15	4.01	3.16
15	2.98	10.2	24.3	44.9	109	75.6	37.2	18.6	8.85	5.57	4.34
20	3.27	12.7	33.8	69.1	201	131	57.1	26.0	11.6	7.19	5.59
25	3.51	15.2	44.3	97.9	331	203	80.1	33.9	14.4	8.86	6.91
30	3.73	18.2	55.4	131	507	292	106	42.2	17.3	10.6	8.27
35	3.91	21.9	66.8	170	734	399	134	50.9	20.5	12.3	9.63
40	4.03	26.5	78.1	214	1020	523	164	59.8	24.8	14.5	10.9
μ/ρ (cm^2/g)	0.6122	0.2957	0.2125	0.1783	0.1270	0.08768	0.06382	0.04482	0.02895	0.02311	0.02153

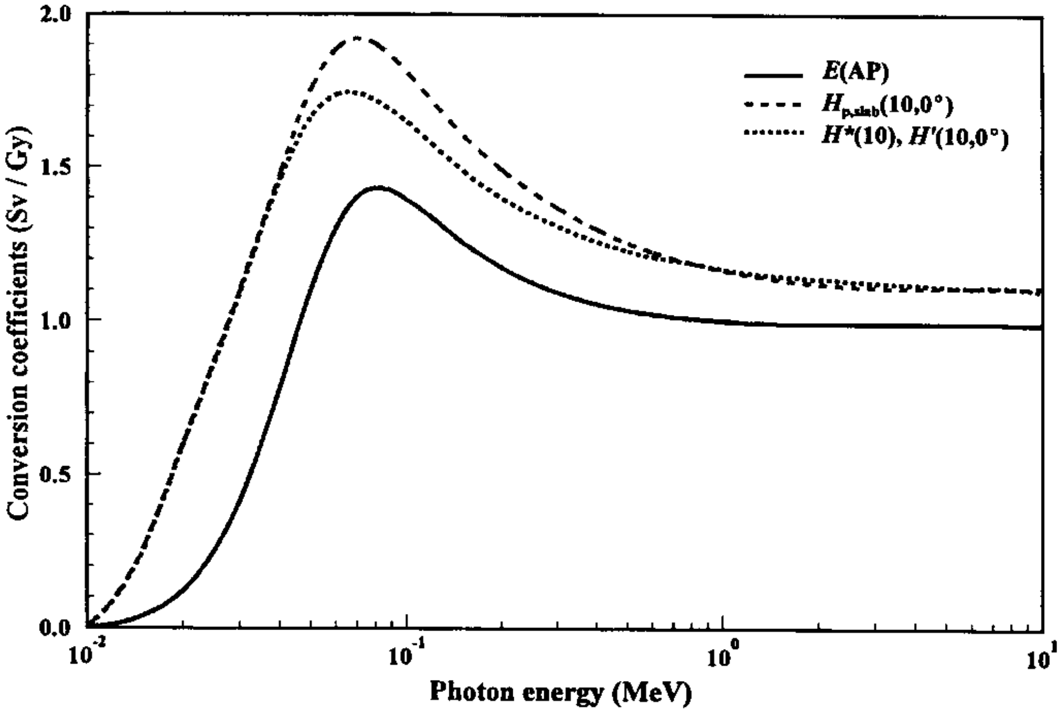
Exposure build-up factors in concrete for isotropic point sources (ANSI).

Broad beam transmission of X-radiation through lead according to ICRP Publication 33, p. 38, fig. 7



Transmission of X-radiation through lead. The X-radiation is produced with an x-ray generator using various DC voltages, a tungsten anode and a 2-mm aluminium filter; the kerma rate per unit of tube current (in mGy/mA.min) through 0 cm of lead is 28.7 at 200 kV, 18.3 at 150 kV, 9.6 at 100 kV, 6.1 at 75 kV, and 2.6 at 50 kV.

Conversion coefficients of Air Kerma to ambient dose equivalent and to effective dose (based on ICRP Publication 74)



Conversion coefficients of Air Kerma (K_a) to ambient dose equivalent H*(10) and to effective dose E(AP).

Scattering coefficients of X-radiation (based on ICRP Publication 33)

Scattering angle	100 kV	200 kV	300 kV
30°	0.02	0.24	0.34
45°	0.03	0.23	0.26
60°	0.04	0.19	0.22
90°	0.05	0.14	0.19
120°	0.12	0.23	0.25
135°	0.17	0.30	0.33
150°	0.21	0.37	0.48

Table 1: Percentage of incident X-radiation that is scattered, measured at 1 m distance from the scattering object, at a field size of 400 cm^2, as a function of the tube voltage and the scattering angle.

MR Implementation Radiation Protection EZ, Article 4.10 paragraph 1,

Article 4.10 Requirements for apparatus

1. The undertaking shall ensure that, as regards inherently safe apparatus:

a. the apparatus is built into a device in such a way that it cannot be in or come into operation when the device is open. To that end the casing of the apparatus is protected, if possible, with switches that automatically break mechanically;

b. the device is used solely when the safety devices affixed to the device to limit radiation levels outside the device are functioning correctly;

c. at no point at 0.1 metres from any accessible surface of the device can a dose equivalent rate greater than 1 microsievert per hour be measured;

d. operation of the device is carried out in a place where the effective dose is less than 1 millisievert per year;

e. the device is provided with a warning symbol.

Figure 1: Test results and spectrum of the liquid waste sample.

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Protocol # 5

Spectraview – Waste sample.lsa

Sample #: 1
Count time: 0.50

REGION	LL	UL	CPM
A	0.0	18.6	72868.0
B	0.0	167.0	272400.0
C	0.0	2000.0	639540.0

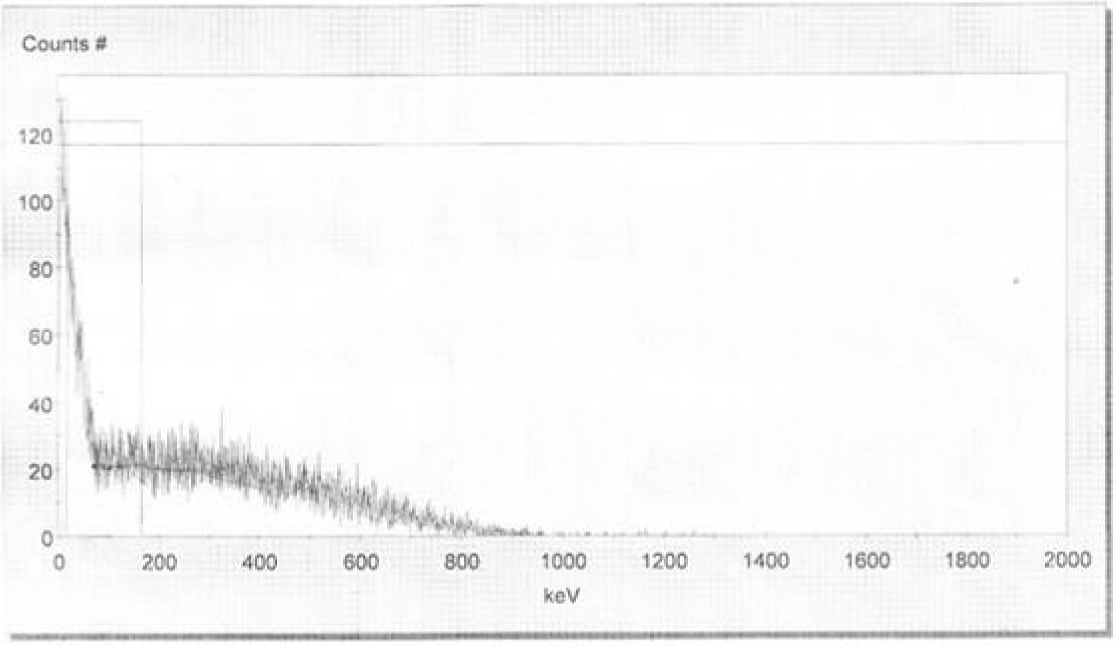

Figure 2: Test results and spectrum of a pure ^{32}P sample

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Protocol # 5

Spectraview - Waste sample.lsa

Sample #: 2
Count time: 0.50

REGION	LL	UL	CPM
A	0.0	18.6	338.4
B	0.0	167.0	3524.0
C	0.0	2000.0	11576.0

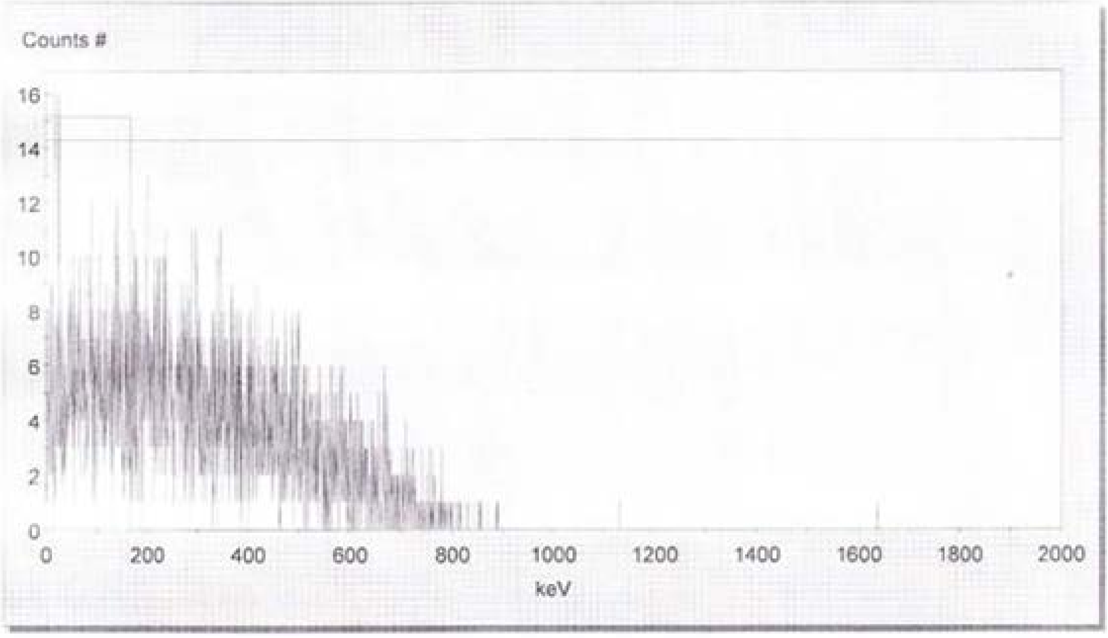

Figure 3: Test results and spectrum of a pure ^{35}S sample

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Protocol # 5
                          Spectraview - Waste sample.lsa

Sample #:       3
Count time:     0.50


REGION          LL            UL            CPM
A               0.0           18.6          4037.5
B               0.0           167.0         9331.3
C               0.0           2000.0        9331.3
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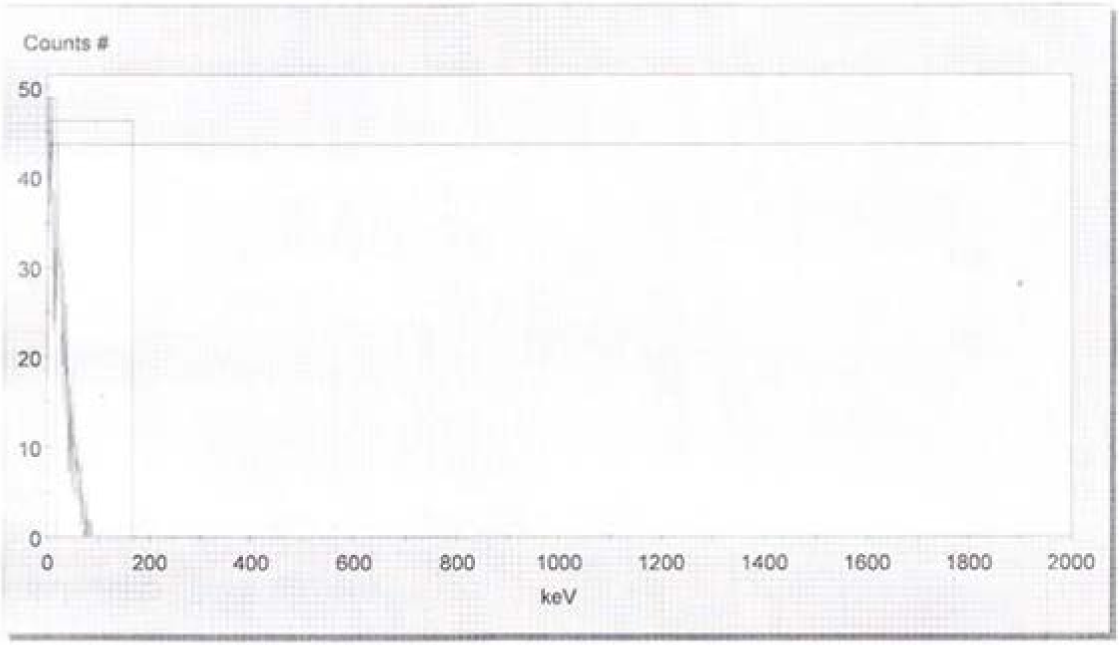

Physical half-life ($T_{½}$), radiotoxicity equivalent for ingestion (Re_{ing}) and maximum beta energy.

Nuclide	**^{3}H**	**^{35}S**	**^{32}P**
$T_{½}$	12.35 years	87.44 days	14.29 days
Re_{ing}	$5.6 \cdot 10^{10}$ Bq	$7.1 \cdot 10^{9}$ Bq	$4.2 \cdot 10^{8}$ Bq
$E_{\square,max}$	18.6 keV	167 keV	1711 keV

MR Implementation Radiation Protection EZ, Appendix 1.5, Section 4.4, Discharges to water

Correction factor (CR_W)
In order to take radioactive decay and accumulation in the environment into account, a correction factor (CR_W) is applied depending on the physical half-life of the relevant radionuclide (see Table 4.9). The discharge of long-lived nuclides is given more weight than the discharge of short-lived ones. The relevant values of CR_{Wi} are supplied in Table 4.9.

Table 4.9 Correction factor (CR_w) for discharges to water, depending on the physical half-life (T½, phys) of the discharged nuclide.

Physical half-life $T_{1/2,\ phys}$	**Correction factor for discharges to water CR_W**
$T_{1/2,\ phys} \leq$ 5 days	0.001
$T_{1/2,\ phys} \leq$ 7.5 days	0.01
$T_{1/2,\ phys} \leq$ 15 days	0.1
$T_{1/2,\ phys} \leq$ 25 years	1
$T_{1/2,\ phys} \leq$ 250 years	10
$T_{1/2,\ phys} >$ 250 years	100

4.4.3 Calculating the maximum annual emissions from a site (W_{max})

The relationship between $A_{W,\ i}$ and $Re_{ing,\ i}$ describes the maximum (theoretically possible) number of radiotoxicity equivalents discharged to water in a year for each radionuclide.

The maximum (theoretically possible) emission to water from a site (W_{max}) is expressed as the number of radiotoxicity equivalents and is obtained after all radionuclides have been summed according to:

$$W_{max} = \sum_{\text{nuclide } i} \frac{A_{W,i}}{Re_{ing,i}} \qquad \textbf{4.8}$$

where:

W_{max} = maximum annual emission to water from a site (expressed in number of Re_{ing}) summed for all discharged nuclides
$A_{W.\ i}$ = maximum (theoretically possible) discharge of radionuclide i to water in a year [Bq]
$Re_{ing,\ i}$ = radiotoxicity equivalent of radionuclide i for ingestion [Bq]

4.4.4 Secondary dose level for discharges to water (W_{SL})

Radioactive substances discharged to a sewer system will not reach the population immediately, but only after a prolonged period during which they will be dispersed throughout the environment. A conservative estimate produces a dilution of a factor of minimum 10^8.
The secondary dose level (W_{SL}) is defined as the discharge (expressed in Re_{ing}) which, according to this approach, causes an ingestion dose equivalent to the SL (1 µSv).
Since the ingestion dose resulting from a discharge to water is assumed to be homogeneously distributed over a large area, W_{SL} is not dependent on the distance between the discharge point and the site boundary (as is the case with emissions to air and A_{SL}).
The value of the secondary dose level for discharges to water (W_{SL}), expressed in Re_{ing}, is equal to:

$$W_{SL} = 100$$