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Dose-rate conversion factors: update

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Abstract : *Dose-rate conversion factors relevant to luminescence and electron spin resonance dating have been derived from values for the energy carried by radiations emitted during nuclear transformations given in the current ENSDF (Evaluated Nuclear Structure Data File). For beta and gamma radiation the factors are a few percent lower than previously used. For the effective alpha dose-rate it is more appropriate to use an approach based on particle ranges and resultant values are given.*

Introduction

In trapped charge dating evaluation of dose-rate is of equal importance to that of palaeodose. In most approaches the dose-rate is derived from measurement of radioelement concentration (or activity) by means of conversion factors, and because these factors are outside the ken of the dating specialist there is a tendency to take them for granted as written in stone. In fact they are based on nuclear data tables and these are in an on-going process of refinement. The tables are dauntingly complex and fortunately for the dating communities a formulation is available in which values for the radiation components of the energy release are given specifically from the dosimetry point of view. The overall tables are known as the *Evaluated Nuclear Structure Data File* (ENSDF) and the dosimetry-orientated formulation known as the Medical Internal Radiation Dose (MIRD) format. These are available on the Brookhaven National Laboratory Web site (http://www.nndc.bnl.gov.) and the International Atomic Energy Authority Web site (http://www-nds.iaea.or.at); except for Table 7 and part of Table 8, the values of the present paper are based on MIRD downloaded on 22nd June 1998. Details about ENSDF has been given by Martin & Blickert-Toft (1970) and by Burrows (1998).

Earlier use of ENSDF was made by Nambi & Aitken (1986) through the dosimetry-orientated format published by the International Commission on Radiation Protection as ICRP-38. Comparison with the values of Nambi & Aitken (1986) is summarized in Tables 4 and 8; since ICRP-38 was based on ENSDF as of 1978 it is not surprizing that there are differences. Prior use of nuclear data tables has been made by Aitken (1974), Aitken & Bowman (1975), Bell (1976, 1977, and 1979), Carriveau & Troka (1978). Subsequent to Nambi & Aitken (1986), re-assessments have been made by Liritzis & Kokkoris (1992) and by Ogoh *et al.* (1993), as discussed in Appendix A.

The paper is primarily written with luminescence dating in mind but it is largely applicable to dating by electron spin resonance as well.

The data

Tables 1, 2 & 3 show the energy emission values and half-lives obtained from the Brookhaven Web site mentioned above for the three radioactive series; Table 4 gives comparison between these data and those presented by Nambi & Aitken (1986). As will be seen there are appreciable decreases in the totals for beta radiation and gamma radiation from the Th-232 series, the principal contributor to these decreases being Ac-228. It is not easy to pinpoint particular measurements that are responsible for decreases; this is because the values are usually based on comprehensive schemes of nuclear energy levels incorporating a number of relevant measurements rather than on single direct measurements.

In Table 5 the emission values have been converted into dose-rate. This is on the usual infinite matrix assumption that the dose-rate is equal to the rate of energy emission per unit mass, implying that there is homogeneity both in radioactive content and

in absorption coefficient. The value given for 'full series' is for the case of radioactive equilibrium, i.e. the disintegration rate of each daughter is equal to that of the parent, except where modified by branching; the value labelled 'pre-Rn' corresponds to 100% escape of radon from the two principal series. This and other types of disequilibrium have been discussed by Krbetschek *et al.* (1994) and Olley *et al.* (1996), among others.

Data for potassium and rubidium are given in Table 6. For potassium, the value for gamma radiation is unchanged from that of Nambi & Aitken (1986) but the value for beta radiation is lower by 4%. For rubidium the beta value is lower by a factor of 1.26; however, except for the internal dose-rate in coarse grains of potassium feldspar, the change is unimportant. The concentration ratio of 200:1 between potassium and rubidium used in Table 6 is an arbitrary choice that is within the range of ratios encountered in samples.

The alpha particle contribution

The luminescence induced by alpha particles per gray of deposited energy is dependent on particle energy, decreasing as the particle energy decreases; this is in contrast to the case for the lightly-ionizing radiations, beta and gamma, for which the effectiveness is independent of energy. Thus in the *k*-value system, developed by Zimmerman (1971), it is necessary to know the precise energy of the alpha particles used for measuring *k* (the ratio of alpha effectiveness compared to that of beta or gamma radiation, effectiveness being the luminescence induced per gray) and also to make allowance for that fact that the alpha particles received during burial have a spectrum that spreads from zero to 8.8 MeV. To do this Zimmerman (1971) introduced *k*(effective) which for quartz he calculated, on the basis of range-energy data then available, as being less than *k*(3.7 MeV) by a factor of 0.86 for the thorium series and 0.80 for the uranium series.

It was implicit in the results of Zimmerman (1971) that, to a first approximation, the luminescence induced per unit length of alpha particle track is independent of particle energy. This was confirmed by Bowman (1976) using the alpha beam from a Van de Graaff generator and in respect of ESR by Lyons & Brennan (1989). This approximation is the basis of the three track-length approaches: the *a*-value system (Aitken & Bowman 1975), the *b*-value system (Bowman & Huntley 1984), and the omnidirectional flux system (Valladas & Valladas 1982). Because the alpha count-rate from a thick layer of sample is proportional to the length of track generated in the sample by its constituent thorium and uranium series this count-rate can be used to give direct determination of the alpha dose-rate during burial. Also required is measurement, for the sample concerned, of the luminescence induced by unit length of track from an artificial source. By comparing this luminescence with that induced per gray of beta (or gamma) radiation, alpha count-rate can be converted to effective alpha dose-rate (see Appendix B). It is 'effective' in the sense of being appropriate for use in the usual age equation in which the palaeodose is expressed in terms of grays of beta (or gamma) radiation.

Although the track-length approaches are conceptually more difficult than the *k*-value system, the latter has the basic disadvantage that there is a need to have an accurate knowledge of the particle energy used in measurement of sample sensitivity. It is not just a matter of energy of the particles emerging from the alpha source; strictly, allowance should also be made for the degradation in energy as the particles penetrate the sample. Hence the preferred values for the effective alpha contribution are those based on track-length as given in Table 7.

Concluding remarks

Although the 8% decrease in the gamma dose-rate from the thorium series is substantial, there is considerable dilution when an actual context is considered, as illustrated in the example of Table 8. For fine-grain dating the total dose-rate is 2.11 according to the present paper compared to 2.18 according to Nambi and Aitken (1986), a decrease of 3%. For coarse-grain dating the values are 1.60 and 1.65 respectively, a decrease of 3% as well. For contexts in which there is dominance by thorium or potassium, the decreases will be greater.

A historical survey of some published conversion factors is given in Appendix A. It will be seen that, for the specimen context of Table 8 at any rate, the totals of the present paper are a few percent lower than all previous ones. However there is no case for diluting the present factors by averaging because the earlier assessments are essentially based on the progenitors of the present ENSDF and these are now superceded. It is reassuring to note that, at any rate for contexts not too dissimilar to the specimen one considered, no dramatic revision is needed in respect of ages based on earlier conversion factors: the highest fine-grain totals, those of Aitken (1974) and Bell (1979), are some 4% higher than that for the present paper; the highest coarse-grain total, that of Aitken (1974) is some 6% higher.

Of course, there are other influences on dose-rate accuracy besides the basic conversion factors, such as related to moisture content, grain-size, radioactive disequilibrium etc. These tend to introduce an uncertainty that is dominant and so the shifts consequent on changing to the factors of the present paper will usually be contained within error limits. Nevertheless, the case for utilization of these factors is just as strong as the case for using state-of-the-art refinements in palaeodose determination. To do otherwise runs the risk of drifting into a situation where there will be two ages for a sample, one based on 'set in stone' factors and another based on the best available data from nuclear physics.

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Table 1: Energy release in the Th-232 decay series

Isotope	Half-life	Alpha	Beta	Gamma
Th-232	14.05 Ga	4.00	-	$<5x10^{-4}$
Ra-228	5.75 a	-	0.01	0.001
Ac-228	6.15 h	-	0.413	0.854
Th-228	1.91 d	5.31	0.019	0.003
Ra-224	3.66 d	5.57	0.002	0.010
Rn-220	55.6 s	6.28	-	0.001
Po-216	0.145 s	6.77	-	$<5x10^{-4}$
Pb-212	10.6 h	-	0.173	0.144
Bi-212	60.6 m	2.14	0.502	0.103
Po-212 (0.641)	0.299 ms	5.63	-	-
Tl-208 (0.359)	3.05 m	-	0.209	1.205
Total		35.7	1.33	2.32
Pre-Rn total		14.9	0.444	0.868

Notes for Table 1

1. Energies are given in MeV and represent the energy emitted per disintegration.
2. Non-SI units used in half-lives: 1a=1 year; 1d=1 day; 1 h=1 hour; 1 m=1 minute
3. Branching ratios are shown in parenthesis against the radioelements in the branches; associated values given for energy release are after adjustment for branching. Note that the branching also affects the energy release of the radioelement at which the bifurcation occurs; thus the value given for the alpha release by Bi-212 is 35.9% of the full energy --- because Tl-208 is formed by alpha emission from Bi-212.
4. Internal conversion and Auger electrons are included with the beta component (which is the average beta energy rather than the maximum). X-rays and annihilation radiation are included with the gamma component. Alpha recoil energies have not been included; this is on the basis that the contribution to luminescence will be negligible on account of the resultant ionization density being even higher than for the alpha particles themselves; the total recoil energy does not exceed 2% of the alpha total for any series. Neutrinos have been ignored because of their very low absorption in matter.
5. A dash indicates that no radiations of that type are listed in MIRD.
6. At-216 has been omitted since its contribution to the total energy is insignificant.

Table 2: Energy release in the U-238 decay series.

Isotope	Half-life	Alpha	Beta	Gamma
U-238	4.468 Ga	4.19	0.007	0.0011
Th-234	24.1 d	-	0.060	0.0093
Pa-234m	1.17 m	-	0.818	0.0161
Pa-234 (0.0016)	6.75 h	-	0.001	0.0023
U-234	246 ka	4.68	0.012	0.0015
Th-230	75.4 ka	4.58	0.013	0.0014
Ra-226	1600 a	4.77	0.0038	0.0074
Rn-222	3.82 d	5.49	-	0.0004
Po-218	3.11 m	6.00	-	-
Pb-214	26.8 m	-	0.294	0.2521
Bi-214	19.9 m	<0.005	0.652	1.4814
Po-214	164 ms	7.68	$<5x10^{-4}$	0.0001
Pb-210	22.3 a		0.033	0.0047
Bi-210	5.01 d	<0.005	0.389	-
Po-210	138.4 d	5.31	$<5x10^{-4}$	$<5x10^{-5}$
Total		42.7	2.28	1.78
Pre-Rn total		18.2	0.906	0.037

Notes for Table 2

1. See notes 1-5 of Table 1.

2. At-218, Rn-218, Tl-210 and Tl-206 have been omitted since their contribution to the total is insignificant

Table 3: Energy release in the U-235 decay series.

Isotope	Half-life	Alpha	Beta	Gamma
U-235	704 Ma	4.27	0.037	0.180
Th-231	25.5 h	-	0.1506	0.028
Pa-231	32.8 ka	4.84	0.032	0.040
Ac-227	21.8 a	0.07	$<5x10^{-4}$	$<5x10^{-4}$
Th-227 (0.986)	18.7 d	5.70	0.028	0.108
Fr-223 (0.014)	21.8 m	-	0.006	0.001
Ra-223	11.4 d	5.67	0.066	0.137
Rn-219	3.96 s	6.63	0.007	0.058
Po-215	1.78 ms	7.39	-	$<5x10^{-4}$
Pb-211	36.1 m	<0.005	0.455	0.064
Bi-211	2.14 m	6.54	0.001	0.047
Tl-207 (0.997)	4.77 m	-	0.494	0.002
Total		41.1	1.27	0.665
Pre-Rn total		20.6	0.319	0.493

Notes for Table 3

1. See notes 1-5 of Table 1.
2. At-215 and Po-211 have been omitted since their contribution to the total is insignificant.

Table 4: Main differences between the current energy per disintegration values and the data presented by Nambi & Aitken (1986).

Isotope	Alpha	Beta	Gamma
Th-232 series:			
Th-232	·	-0.9%	·
Ra-228	·	-0.5%	·
Ac-228	·	-4.5%	-4.6%
Bi-212	·	+2.2%	-3.3%
Total	-0.7%	-4.4	-8.3%
U-238 series:			
Bi-214	·	·	-1.5%
Total	-0.4%	-1.2%	-1.2%
U-235 series:			
Total	-1.2%	-8.6%	+5.6%

Notes for Table 4

1. Percentages are with respect to the total for the radiation type concerned of the series using Nambi & Aitken (1986) values as base. All are decreases except for the beta emission from Bi-212, and the gamma from the U-235 series
2. The only individual isotopes shown are those which contribute more than 0.5% change in the total for the radiation type of the series.

Table 5: Dose-rate data for the thorium and uranium series

	Th-232	**U-238**	**U-235**	**Nat. U**
1. Abundance by weight	100%	99.29%	0.71%	-
2. Half-life [Ga]	14.05	4.468	0.704	-
3. Parent activity [Bq mg^{-1}]	4.06	12.4	80	12.9
4. Activity share in nat. U	-	95.6%	4.4%	-
Dose-rate [Gy ka^{-1}] per ppm				
5. alpha, full series	0.732	2.685	16.6	2.78
6. alpha, pre-Rn	0.305	1.146	(16.6)	1.26
7. beta, full series	0.0273	0.143	0.515	0.146
8. beta, pre-Rn	0.0091	0.057	(0.515)	0.060
9. gamma, full series	0.0476	0.112	0.269	0.113
10. gamma, pre-Rn	0.0178	0.0025	(0.269)	0.0044
To obtain dose-rate [Gy ka^{-1}] per unit specific activity of parent [Bq kg^{-1}]				
11. Divide lines 5-10 by	4.06	12.4	80	12.9

Notes for Table 5

1. The rows labelled 'pre-Rn' give the values for 100% escape of radon in the case of the Th-232 and U-238 series, but because of the short half-life of Rn-219 the values given for U-235 and natural U include contributions of that gas and its daughters.

2. Dose-rate values are based on Table 1, 2 and 3.

3. 'ppm' equals mg of parent per kg of sample.

4. The weight abundances given in row 1 for U-238 and U-235 correspond to the natural atomic abundances of 99.28% and 0.72% respectively.

Table 6: Dose-rate data for potassium and rubidium

	K-40	**Rb-87**
1. Natural abundance [mg/g]	0.119	283
2. Half-life [Ga]	1.277	47.5
3. Average energy per disintegration [MeV]	β: 0.501 γ: 0.156	β: 0.082
4. Specific activity [Bq kg^{-1}] for concentration of 1% natural K and 50 ppm natural Rb	β: 270 γ: 32.5	β: 45.29
5. Dose-rate [Gy ka^{-1}] for concentrations as in 4	β: 0.782 γ: 0.243	β: 0.019
6. As in 5 but for 1% K_2O and 50 ppm Rb_2O	β: 0.649 γ: 0.202	β: 0.017

Notes for Table 6

1. The energy given is that released per disintegration, i.e. after allowance for branching between beta and gamma (89.3% and 10.7% respectively).
2. The contents given in row 1 correspond to natural atomic abundances of 116.7 ppm and 27.8%.

Table 7: Alpha particle data and effective dose-rates

	Th-232	U-238	U-235	nat. U
Average alpha ranges [μg mm^{-2}]:				
1. Full series	67.4	56.7	65.9	-
2. pre-Rn	51.2	44.6	(65.9)	-
Effective number of full alpha emissions per parent disintegration:				
3. Full series	6	8	7	-
4. pre-Rn	3	4	(7)	-
Count-rate [ks^{-1}] per [Bq kg^{-1}] of parent, 42-mm diameter scintillator:				
5. Full series	0.119	0.129	0.136	0.129
6. pre-Rn	0.0426	0.0482	(0.136)	0.0521
Count-rate [ks^{-1}] for 1 ppm of parent, 42-mm diameter scintillator:				
7. Full series	0.483	1.60	10.9	1.67
8. pre-Rn	0.173	0.599	(10.9)	0.672
Share of counts in natural uranium				
9. Full series		95.4%	4.6%	
10. pre-Rn		88.5%	11.5%	
Dose-rate [Gy ka^{-1}] for count-rate = 10 ks^{-1}, 42-mm diameter scintillator:				
11. Effective α, a=0.1, full series	1.26	1.31	1.26	1.31
12. Effective α, a=0.1, pre-Rn	1.31	1.35	(1.26)	1.34
13. beta, full series	0.565	0.893	0.475	0.874
14. beta, pre-Rn	0.528	0.951	(0.475)	0.896
15. gamma, full series	0.986	0.697	0.248	0.676
16. gamma, pre-Rn	1.03	0.0387	(0.248)	0.0627
Effective alpha dose-rate [Gy ka^{-1}] per 1 ppm of parent, a = 0.1:				
17. Full series	0.0611	0.210	1.37	0.218
18. pre-Rn	0.0227	0.0808	(1.37)	0.090

Notes for Table 7

1. The ranges were obtained by adding 2% to the ranges evaluated for quartz by Brennan & Lyons (1989) using the data of Ziegler *et al.* (1985); the extra 2% makes allowance for the higher average atomic weight to be expected in typical sediment. For the pottery composition considered by Brennan & Lyons (1989) the ranges were 5% greater than for quartz. No adjustment in range has been made on account of the slightly different alpha energies noted in Table 4.

2. The range values given by Aitken (1998) are between 6% and 7% higher than those given in the Table. This is on account of use by that author of the values given by Valladas (1988) which were based on Zeigler (1977) rather than Zeigler *et al.* (1985). There are corresponding differences in subsequent count-rates and dose-rates but the effective alpha dose-rates per unit count-rate are not affected because both are proportional to range.

3. The count-rates are for a sample that is alpha-thick and for a scintillator with an area of 13.85 cm^2. It is assumed that the efficiency of the scintillator is 100%, i.e.that every incident particle gives rise to an output pulse from the

photomultiplier; however it should be noted that studies by Woithe & Prescott (1995) indicate that the efficiency of a typical ZnS screen may be only about 90%.

4. The assumed electronic threshhold setting is such that for a sample containing only the Th-232 series, 85% of the pulses from the photomultiplier are recorded; with this setting the corresponding values are 82% for U-238 and 85% for U-235; for the pre-Rn parts of the first two series the values are 80% and 78% respectively.

5. Rows 13-16 utilize the data of rows 7 and 8 together with the data of Table 5, but rows 11, 12, 17, and 18 are based on the a-value system; for the b-value system, note that $b = 13a$ when the units of b are Gy μm^2. Values of 0.90 and 0.88, for the full series and for the pre-Rn parts respectively, have been used for η, the efficiency factor (see Appendix B).

Table 8 Comparative dose-rates [Gy ka^{-1}] for a specimen context

		Dose-rates				
	Concentration	**effective alpha**	**beta**	**gamma**	**Fine-grain total**	**Coarse grain total**
K	1%	-	0.782 (0.814)	0.243 (0.243)	1.025 (1.058)	0.947 (0.976)
Rb	50 ppm	-	0.019 (0.023)	-	0.019 (0023)	0.014 (0.018)
Th	3 ppm	0.183 (0.190)	0.082 (0.086)	0.143 (0.156)	0.408 (0.433)	0.217 (0.234)
Nat. U	1 ppm	0.218 (0.222)	0.146 (0.147)	0.113 (0.114)	0.477 (0.489)	0.244 (0.246)
Cosmic	-	-	-	0.18	0.18	0.18
Totals	-	0.401 (0.413)	1.029 (1.071)	0.679 (0.693)	2.11 (2.18)	1.60 (1.65)

Notes for Table 8

1. The values are those from Tables 5, 6, and 7 of the present paper and from Tables 4 and 5 of Nambi & Aitken (1986), the latter being in parenthesis. The effective alpha dose-rates for the former are for $a = 0.1$ (as in Table 7) and those for the latter are derived using $k = 0.1$ and conversion factors to k(effective) of 0.86 and 0.80 for Th and U respectively.

2. Since it is highly penetrating it is convenient to list cosmic radiation under 'gamma'. The value quoted is appropriate to a depth of a metre.

3. In the totals for coarse-grain dating an attenuation factor of 0.90 has been used for the beta contributions except in the case of Rb for which the factor has been arbitrarily taken to be 0.75 on account of the lower penetration (appropriate evaluation of this factor is not available).

4. The moisture content is assumed to be zero.

Appendix A : Historical survey

Table A.1 gives values for the specimen context of Table 8 based on conversion factors published from 1974 onwards; the publications listed have been restricted to those that embody a primary assessment of nuclear data tables.

It should be noted that the date of the publication is often somewhat later than that of the nuclear data tables on which the factors are based; thus the source data for Aitken (1974) were from tables of 1967, those for Nambi & Aitken (1986) were from ENSDF as at 1978, and the sources used by Liritzis & Kokkoris (1992) have publication dates of 1983 and 1986. As noted earlier the source data for the present paper are from ENSDF as at mid-1998; hence the source data span three decades and the consistency is remarkable.

Table A.1: Annual dose-rates in [Gy ka^{-1}] for a specimen context: historical summary

K: 1%	Rb: 50 ppm	Th: 3ppm	U: 1ppm	Total fine	Total coarse
Aitken (1974)					
1.122	-	0.445	0.456	2.20	
1.035	-	0.259	0.225		1.70
Aitken & Bowman (1975)					
1.106	-	0.412	0.470	2.17	
1.019	-	0.216	0.232		1.65
Bell (1976)					
1.069	-	0.428	0.501	2.18	
0.986	-	0.228	0.259		1.65
Bell (1977)					
1.069	-	0.430	0.489	2.17	
0.986	-	0.231	0.246		1.64
Bell (1979)					
1.080	0.025	0.430	0.489	2.21	
0.997	0.019	0.231	0.246		1.67
Carriveau & Troka (1978)					
1.050	0.019	0.407	0.498	2.16	
0.970	0.014	0.209	0.255		1.63
Nambi & Aitken (1986)					
1.058	0.023	0.433	0.489	2.18	
0.976	0.018	0.234	0.246		1.65
Liritzis & Kokkoris (1992)					
1.068	0.025	0.422	0.490	2.19	
0.986	0.019	0.226	0.243		1.65
Adamiec & Aitken (1998)					
1.025	0.019	0.408	0.477	2.11	
0.947	0.014	0.217	0.244		1.60

Notes for Table A.1

1. The values are for the same specimen context as for those of Table 8, with the same parameters. As in that table the totals include a cosmic-ray contribution of 0.18 Gy/ka.
2. The first row under each publication is for fine-grain dating and the second for coarse-grain dating.
3. Conversion factors have also been derived by Ogoh *et al.* (1993) using the basic data of Liritzis & Kokkoris (1992). The factors derived are within 1% of those of the latter except that the alpha dose-rate from uranium is lower by 1.4% and the beta dose-rate from rubidium is higher by 1.7%. The resultant values appropriate to Table A.1 are all within 1% of those of Liritzis & Kokkoris (1992) except in respect of rubidium.

Appendix B : Conversion of various entities

Below we give the expressions which were used to calculate and convert various values used in this paper.

1) **Conversion of oxide content to elemental content**

Table B.1: Conversion of weight content: oxide to element

Oxide	Element	Atomic weight	Equivalent element content
K_2O	K	39.10	0.8301
Rb_2O	Rb	85.5	0.9144
ThO_2	Th	232.0	0.8788
UO_3	U	238.0	0.8322

2) **Conversion of atomic to weight abundance**

Atomic abundance gives the percentage of atoms of different isotopes in the natural sample. If the atomic abundance of i-th isotope is r_i, the average atomic weight is M_{av} and the atomic weight of the isotope is m_i then the weight abundance of this isotope will be

$$R_i = \frac{m_i}{M_{av}} \times r_i \qquad \text{(B.1)}$$

3) **Parent activity A_P in units of [Bq mg^{-1}] :**

$$A_P = \frac{\lambda \ N_A}{M} \times 10^{-3} \qquad \text{(B.2)}$$

where N_A is the Avogadro number (6.022 x 10^{23}), M is the atomic weight of the parent and λ is the decay constant ($\lambda = \ln 2/\tau_{1/2}$, $\tau_{1/2}$ is the half-life in seconds, 1 year = 31.56 x 10^6 s, 1 Bq=1 disintegration per second)

4) **Dose rate [Gy ka^{-1}] per ppm by weight of parent element**

$$\dot{D} = 5.056 \times A_P E_P \times 10^{-3} \qquad \text{(B.3)}$$

where E_P is energy release in the series per parent disintegration expressed in [MeV]. The numerical factor is based on 1 [MeV] = 1.602 x 10^{-13} [J]

5) **Dose rate in [Gy ka^{-1}] when parent activity is given:**

$$\dot{D} = 5.056 \times E_P c \times 10^{-3} \qquad \text{(B.4)}$$

where c is the specific activity of parent in the sample in [Bq kg^{-1}].

6) **Alpha count-rate when parent activity is given**

If C Bq kg^{-1} is the activity of parent, the thick-source alpha count-rate [ks^{-1}] is equal to

$$\dot{\alpha} = \frac{1}{4} fAR\rho \, nC \times 10^{-4} \qquad \text{(B.5)}$$

where f is the electronic threshold fraction, A cm^2 is the area of the scintillator, $R\rho$ is the average (projected) range expressed in [μg mm^{-2}], and n is the effective number of alpha emissions.

7) Effective alpha dose-rate

As explained in various sources, such as Aitken & Bowman (1975), Bowman & Huntley (1984) or Aitken (1985), the effective alpha dose-rate is given by

$$D' = 31.56 \times \eta\, bR'\rho\, nc \times 10^{-6} \qquad \text{(B.6)}$$

where η is the efficiency factor that makes allowance for the lower average energy of the natural spectrum experienced during burial compared to the particle energy used for measurement of alpha sensitivity (see note 5 of Table 7), b [Gy μm^2] is the dose of beta (or gamma) radiation required to induce the same luminescence, in the sample concerned, as an alpha track density of 1 [μm^{-2}], and $R'\rho$ is the average *total* range which is taken as $1.008 \times R\rho$ on the basis that the difference is approximately 0.4 [μg mm^{-2}] (Brennan & Lyons 1989).

Hence from (B.5), and changing to the a-value system by putting $b = 13a$,

$$D' = 16.54 \times \frac{\eta\, a}{fA} \times \alpha \qquad \text{(B.7)}$$

For measurement of either a or b it is necessary to have an alpha source calibrated in terms of track-length delivered and to have sufficient separation between source and sample that appreciably oblique particles are avoided; both source and sample must be in vacuum; the energy of the incident particles needs to be in the range 4-6 MeV and the layer of sample needs to be thin enough for emergent particles to have an energy of not less than 2 MeV.

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