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A RE-EVALUATION OF RADIATION DOSE-RATE CONVERSION FACTORS

Liritzis, I.[1], Stamoulis, K.[2], Papachristodoulou, C.[3], and Ioannides, K.[2,3]

[1]University of the Aegean, Lab of Archaeometry, Dept of Mediterranean Studies,
1 Demokratias Str, Rhodes 85100, Greece
[2]Archaeometry Center, University of Ioannina, 451 10 Ioannina, Greece
[3]Dept of Physics, University of Ioannina, 451 10 Ioannina, Greece

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Corresponding author: liritzis@rhodes.aegean.gr

ABSTRACT

It has been about forty years since the dose-rate conversion factors commenced to appear in tabular forms and, ever since, periodical updates have been published. The present work contributes to this continuous updating, using the latest evaluated nuclear data for the ^{238}U-, ^{235}U- and ^{232}Th-series, as well as for ^{40}K and ^{87}Rb, obtained from the Evaluated Nuclear Structure Data File (ENSDF) database and the Nuclear Wallet Cards. An estimate of the accuracy of the dose-rate conversion factors is further attempted for the first time, by taking into account individual uncertainties in all quantities involved in the calculations.

A literature comparison between all previously published dose-rate conversion factors is presented and their Historical Mean (*HM*) values are calculated. The standard deviation from the *HM* is introduced as a measure of the fluctuation in individual updates. A selected example is given to show that the use of the HM instead of the present dose-rate conversion factors has a minimal impact on dating calculations performed by the thermoluminescence, the optically stimulated luminescence and the electron spin resonance methods. It is concluded that there is no justification in periodically reviewing the dose-rate conversion factors and thus, the present values can be considered as a revised overview that future dating applications should safely rely upon.

KEYWORDS: dose-rate, luminescence, dating, conversion, U, Th, K, Rb, historical mean, updating

INTRODUCTION

The luminescence (Thermoluminescence-TL and Optically Stimulated Luminescence-OSL) and Electron Spin Resonance (ESR) dating methods rely upon the accurate determination of the accumulated radiation dose over an elapsed time and the rate at which this dose has been delivered to the material under study, i.e.:

Age=Equivalent Dose/Annual Dose Rate (1)

To assess the denominator in eq. (1), the concentration or the activity of radioelements is measured and then converted to dose-rate using appropriate conversion factors. The calculation of these conversion factors is a tedious task that takes into account a long list of nuclear data, such as radioactive half-lives, branching ratios, energies and intensities of the alpha, beta and gamma radiation emitted during individual transitions in the naturally-occurring uranium-series, the thorium-series, potassium-40 and rubidium-87. Thus, dating specialists typically resort to tabulated values available in the literature. Since 1975, a series of dedicated papers have been published reporting dose-rate conversion factors and their updates (Aitken and Bowman, 1975; Carriveau and Troka, 1978; Bell, 1976, 1977, 1979; Aitken, 1985; Nambi and Aitken, 1986; Liritzis and Kokkoris, 1992; Kokkoris and Liritzis, 1997; Aitken, 1998; Adamiec and Aitken, 1998; and Guérin et al., 2011).

The present work aims to contribute to this continuous updating, using the latest evaluated nuclear data and introducing for the first time an estimate of the accuracy of the dose-rate conversion factors. To this end, the uncertainties in all quantities involved in the calculations are taken into account and the associated total uncertainty is determined by error propagation.

THE DATA

The nuclear data used for the present calculations were obtained in May 2012 from the Evaluated Nuclear Structure Data File (ENSDF) database and Nuclear Wallet Cards, available at the Brookhaven National Laboratory (BNL) Web site (http://www.nndc.bnl.gov).

The dose-rate (D), in Gy s^{-1}, is calculated as:

$$D = A\overline{E}\ \frac{MeV}{g\,s}\times 1.60218\times 10^{-13}\ \frac{J}{MeV}\times 10^{3}\ \frac{g}{kg} \quad (2)$$

where A is the activity concentration of the parent radionuclide, in Bq g^{-1}, and is the average energy (alpha, beta or gamma), in MeV per disintegration.

The beta component (average beta energy), includes Auger electrons and internal conversion; the gamma component includes X-rays and annihilation radiation; the alpha recoil and neutrinos are not included due to their insignificant contribution to dose-rates (Adamiec and Aitken, 1998).

To determine the uncertainty (denoted as σ) in dose-rate values, individual uncertainties in all involved quantities – such as half-lives, energies, intensities, branching ratios, atomic abundances etc. – were taken into account and combined using standard error propagation formulas.

The calculations are catalogued in easily accessible tabular forms, following the approach of Guérin et al. (2011). Tables 1 and 2 show the energy emission and dose rate values for the ^{238}U and ^{235}U series and for the ^{232}Th series, respectively. Data for potassium and rubidium are listed in Table 3.

Compared with the most recent update published by Guérin et al. (2011), the present dose-rates show slight differences, typically well below 0.5%, with one main exception of the gamma dose-rates for ^{235}U (see Table 4). These differences, however, are within the uncertainty calculated for the present dose-rate values, which is given as σ (%) in Table 4.

DISCUSSION

A detailed historical survey of published dose-rate conversion factors is presented in Tables 5-7 and further illustrated in Figs 1-6. For the needs of comparison, a "Historical Mean" (HM) dose-rate value has been introduced, which is defined as the arithmetic mean of all previously reported dose-rates for each of the alpha, beta and gamma components and for each of the parent radionuclides (^{238}U, ^{235}U, ^{232}Th, ^{40}K, ^{87}Rb). The standard deviation from the mean is also calculated and given as the uncertainty (1σ) in the individual *HM* values. The inspection

of Figs 1-6 shows that, in principle, published dose-rates fluctuate smoothly within the HM 1σ range; pronounced deviations are evidenced only for some dose-rate values.

To demonstrate how the discrepancies between the dose-rate conversion factors, due to nuclear data updates, influence the age calculations of a specific sample with a measured natural OSL signal (and a calculated equivalent dose), we assumed that a typical dating sample, a ceramic sherd, was buried in a geological stratum of typical natural radioactivity, 21 Bq kg^{-1} ^{238}U or 1.687 ppm, 1 Bq kg^{-1} ^{235}U or 0.0125 ppm (or total Uranium 1.7 ppm), 40 Bq kg^{-1} ^{232}Th or 10 ppm Thorium, 1% of natural K and 50 ppm of natural Rb. In the case of the ^{238}U, ^{235}U and ^{232}Th decay series, we assumed that they were in equilibrium states. For the purpose of simplicity, we also assumed that the single-aliquot regenerative-dose (SAR) protocol was followed (Murray and Wintle, 2000). In our example there is no need to consider the influence of alpha emission dose-rate because quartz grains (100-150 μm) in the sample are usually etched by a 40% HF solution and the outer portion of the grains, where the alpha energy was delivered and stored as the OSL producing signal, is removed. Tabulated conversion factors are usually expressed in Gy ka^{-1} per ppm of the parent radioisotope in the case of ^{238}U, ^{235}U and ^{232}Th. In many cases the determination of the uranium, thorium and potassium radioisotopes is performed with gamma spectroscopy and thus the concentrations are expressed as Bq kg^{-1} dry matter of sample. The conversion factors can be expressed in Gy ka^{-1} per Bq kg^{-1} using the activities of the isotopes per ppm. These values are 12.447 Bq kg^{-1} per 1 ppm of ^{238}U, 80.030 Bq kg^{-1} per 1 ppm of ^{235}U and 4.058 Bq kg^{-1} per 1 ppm of ^{232}Th. Regarding uranium isotopes ^{238}U and ^{235}U, the total natural uranium radioactivity corresponds to 12.927 Bq kg^{-1} per 1 ppm. In the case of ^{40}K, the conversion factors are expressed as Gy ka^{-1} per 1% of natural K, which corresponds to 317.38 Bq kg^{-1} and in the case of ^{87}Rb as Gy ka^{-1} per 50 ppm, which corresponds to 44.8 Bq kg^{-1}.

Using the above values and the appropriate dose-rate conversion factors, the total dose-rate delivered on a quartz grain inside the sherd from the surrounding soil can be determined. Calculations were performed based on all previously published conversion factors, as well as on those derived in the present update. The results presented in Table 8 (see also Fig. 7) show that the dose-rate based on the conversion factors assessed in the present work, coincides with the dose-rate based on the Historical Mean in the range of the associated errors.

In the case when fine grains of quartz are used for the equivalent dose estimation (<100 μm), the stage of HF etching and feldspar elimination is omitted. Thus, the contribution of alpha natural radioactivity in the dose delivered to the quartz grains should be taken into account. The additional dose from alpha particles derived from the decay chains of uranium and thorium radioisotopes should be included in the calculations. If so, the estimated dose rates change drastically and the values presented in Table 8, based on present work dose conversion factors should be replaced by 5.20 ± 0.04 Gy ka^{-1} for ^{238}U and ^{235}U (total natural uranium), 8.01 ± 0.03 Gy ka^{-1} for ^{232}Th and 14.28 ± 0.05 Gy ka^{-1} for the total dose rate.

It could be concluded that the total dose-rate did not vary significantly through the last 37 years (1975-2012), although most of the nuclear data the calculations are based on, have been re-evaluated through these years.

Considering the influence of the natural radioactivity components (due to uranium isotopes, thorium, potassium and rubidium) on the total calculated dose-rate, it must be noted that significant differences in values following re-evaluations of nuclear data are observed only in the case of the ^{232}Th-series. Thus, the changes in the total dose-rate conversion factors through past years are associated mainly with the re-evaluations of the ^{232}Th-series nuclear data.

On the basis of the HM introduced in this work, it may be argued that any future refinement of nuclear data is unlikely to provide any significant improvement of dose-rate conversion factors.

A final concern related to the annual dose determination should be raised at this point. In the example illustrated above, as in most luminescence dating applications, secular equilibrium in the decay chains through time was assumed, implying that the dose rate remains constant

over the burial period. However, increasing evidence of widespread disequilibrium has been reported for several depositional contexts and the implications on dose rate assessment should be considered in dating studies, as important discrepancies in age determination can occur depending on the origin of the disequilibrium and its kinetics (see for example Guibert et al., 2009; Lahaye et al., 2012; Kokkoris and Liritzis, 1997; Danali – Cotsakis and Liritzis, 1985 and references therein). Disequilibrium in the decay chain of ^{232}Th is unlikely to be important in most natural materials, given the short half-lives of the longest-lived daughters in the chain, i.e. ^{228}Ra (5.75 y) and ^{228}Th (1.91 y). In contrast, because of the much longer half-lives of many of the ^{238}U daughters (^{234}U, ^{230}Th, ^{226}Ra), disequilibrium should perhaps be expected, particularly in surficial environments or "open systems" in which solution and precipitation processes may significantly disturb the initial state of mobile radionuclides. Once the nature and extent of disequilibria in the U-series have been established, the tabulated dose conversion factors should be considered separately for each radionuclide in the decay chain in order to estimate the mean annual dose rate used in the age calculation.

CONCLUDING REMARKS

Dose-rate conversion factors have been recalculated using the latest nuclear data for the naturally-occurring uranium-series, the thorium-series, potassium-40 and rubidium-87. Although revision of these calculations has been considered a self-evident task throughout the last four decades, a critical evaluation of the updating process has been attempted in the present work. The comparison between the present calculations and the Historical Mean of previously published updated values suggested that the continuous updating of dose-rate conversion factors is rather unnecessary. The values given in this work may be safely used, as they are the last updates and the only ones which include error estimation. The error in dose-rate conversion factors may be considered to have a marginal contribution to the error in age calculations, compared to other interfering uncertainties.

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Table 1. Energy release and dose rates in the uranium (^{238}U and ^{235}U) decay series.

Isotope	Half-life (s)	σ	Alpha						Beta						Gamma					
			Energy	σ	Dose rate	σ	Dose rate nat. U	σ	Energy	σ	Dose rate	σ	Dose rate nat. U	σ	Energy	σ	Dose rate	σ	Dose rate nat. U	σ
^{238}U	1.41E+17	9.46E+13	4.191	0.177	0.264	0.011	0.262	0.011	0.007	0.001	0.0004	0.0000	0.0004	0.0000	0.001	0.000	0.0001	0.0000	0.0001	0.0000
^{234}Th	2.08E+06	2.59E+03							0.059	0.002	0.0037	0.0001	0.0037	0.0001	0.008	0.000	0.0005	0.0000	0.0005	0.0000
^{234m}Pa	6.95E+01	6.60E-01							0.812	0.002	0.0510	0.0001	0.0507	0.0001	0.016	0.000	0.0010	0.0000	0.0010	0.0000
^{234}Pa	2.41E+04	1.80E+02							0.000	0.000	0.0000	0.0000	0.0000	0.0000	0.000	0.000	0.0000	0.0000	0.0000	0.0000
^{234}U	7.74E+12	1.89E+10	4.752	0.009	0.299	0.001	0.297	0.001	0.011	0.000	0.0007	0.0000	0.0007	0.0000	0.001	0.000	0.0001	0.0000	0.0001	0.0000
^{230}Th	2.38E+12	9.46E+09	4.664	0.015	0.293	0.001	0.291	0.001	0.012	0.001	0.0008	0.0000	0.0008	0.0000	0.001	0.000	0.0001	0.0000	0.0001	0.0000
^{226}Ra	5.05E+10	2.21E+08	4.773	0.005	0.300	0.000	0.298	0.000	0.004	0.000	0.0002	0.0000	0.0002	0.0000	0.007	0.000	0.0005	0.0000	0.0005	0.0000
^{222}Rn	3.30E+05	2.59E+01	5.489	0.001	0.345	0.000	0.343	0.000							0.000	0.000	0.0000	0.0000	0.0000	0.0000
^{218}Po	1.86E+02	7.20E-01	6.001	0.000	0.377	0.000	0.375	0.000												
^{214}Pb	1.61E+03	5.40E+01							0.291	0.005	0.0183	0.0003	0.0182	0.0003	0.239	0.002	0.0150	0.0001	0.0149	0.0001
^{214}Bi	1.19E+03	2.40E+01	0.001	0.000	0.000	0.000	0.000	0.000	0.660	0.003	0.0415	0.0002	0.0412	0.0002	1.476	0.002	0.0928	0.0001	0.0921	0.0001
^{214}Po	1.64E-04	2.00E-06	7.685	0.000	0.483	0.000	0.480	0.000							0.000	0.000	0.0000	0.0000	0.0000	0.0000
^{210}Pb	7.00E+08	6.94E+06							0.033	0.001	0.0021	0.0000	0.0021	0.0000	0.005	0.000	0.0003	0.0000	0.0003	0.0000
^{210}Bi	4.33E+05	4.32E+02							0.389	0.000	0.0245	0.0000	0.0243	0.0000						
^{210}Po	1.20E+07	1.73E+02	5.304	0.000	0.334	0.000	0.331	0.000	0.000	0.000	0.0000	0.0000	0.0000	0.0000	0.000	0.000	0.0000	0.0000	0.0000	0.0000
^{238}U, total			42.86	0.178	2.696	0.011	2.676	0.011	2.278	0.007	0.1433	0.0004	0.1422	0.0004	1.755	0.003	0.1104	0.0002	0.1096	0.0002
^{238}U, pre-radon			18.38	0.178	1.156	0.011	1.148	0.011	0.904	0.002	0.0569	0.0002	0.0565	0.0002	0.0348	0.0004	0.0022	0.0000	0.0022	0.0000
^{235}U	2.22E+16	1.58E+13	4.116	0.163	1.664	0.066	0.0118	0.0005	0.033	0.0015	0.0134	0.0006	0.0001	0.0000	0.1645	0.0016	0.0665	0.0006	0.0005	0.0000
^{231}Th	9.19E+04	1.58E+13							0.142	0.0210	0.0573	0.0085	0.0004	0.0001	0.0230	0.0019	0.0093	0.0008	0.0001	0.0000
^{231}Pa	1.03E+12	1.58E+13	4.367	0.013	1.766	0.006	0.0126	0.0000	0.031	0.0016	0.0127	0.0006	0.0001	0.0000	0.0396	0.0012	0.0160	0.0005	0.0001	0.0000
^{227}Ac	6.87E+08	1.58E+13	0.070	0.001	0.028	0.001	0.0002	0.0000	0.012	0.0007	0.0049	0.0003	0.0000	0.0000	0.0006	0.0000	0.0002	0.0000	0.0000	0.0000
^{227}Th	1.61E+06	7.78E+03	5.820	0.095	2.353	0.039	0.0167	0.0003	0.046	0.0065	0.0187	0.0026	0.0001	0.0000	0.1565	0.0048	0.0633	0.0019	0.0005	0.0000
^{223}Fr	1.32E+03	4.20E+00							0.009	0.0005	0.0037	0.0002	0.0000	0.0000	0.0008	0.0001	0.0003	0.0000	0.0000	0.0000
^{223}Ra	9.88E+05	4.32E+03	5.665	0.083	2.291	0.034	0.0163	0.0002	0.063	0.0006	0.0254	0.0002	0.0002	0.0000	0.1352	0.0012	0.0547	0.0005	0.0004	0.0000
^{219}Rn	3.96E+00	1.00E-02	6.742	0.088	2.726	0.035	0.0194	0.0003	0.006	0.0000	0.0026	0.0000	0.0000	0.0000	0.0582	0.0023	0.0235	0.0009	0.0002	0.0000
^{215}Po	1.78E-03	4.00E-06	7.392	0.002	2.989	0.002	0.0213	0.0000												
^{211}Pb	2.17E+03	1.20E+01							0.450	0.0023	0.1818	0.0009	0.0013	0.0000	0.0637	0.0006	0.0258	0.0002	0.0002	0.0000
^{211}Bi	1.28E+02	1.20E+00	6.549	0.013	2.641	0.005	0.0188	0.0000	0.000	0.0000	0.0002	0.0000	0.0000	0.0000	0.0456	0.0004	0.0184	0.0002	0.0001	0.0000
^{211}Po	5.16E-01	3.00E-03	0.021	0.000	0.008	0.000	0.0001	0.0000	0.000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0449	0.0009	0.0182	0.0004	0.0001	0.0000
^{207}Tl	2.86E+02	1.80E+00							0.492	0.0021	0.1988	0.0009	0.0001	0.0000	0.0658	0.0006	0.0266	0.0003	0.0005	0.0000
^{235}U, total			40.742	0.225	16.474	0.091	0.117	0.001	1.283	0.0224	0.5190	0.0090	0.0037	0.0001	0.7536	0.0062	0.3047	0.0025	0.0022	0.0000
Total							2.793	0.011					0.1459	0.0004					0.1118	0.0002
Pre-radon, total							1.265	0.011					0.0602	0.0002					0.0044	0.0000

Notes:
1. Energies are given in MeV and represent the energy emitted per disintegration.
2. Dose-rates are given in Gy ka^{-1} per ppm of parent, assuming equilibrium in the decay chains.
3. Branching ratios are (0.16±0.04)% for ^{234}Pa, (99.84±0.04)% for ^{234}U, (99.980±0.002)% for ^{214}Pb, (99.979±0.001)% for ^{214}Po, (98.620±0.004)% for ^{227}Th, (1.380±0.036)% for ^{223}Fr, (0.276±0.004)% for ^{211}Po and (99.724±0.004)% for ^{207}Tl.
4. The row labeled "^{238}U, pre-radon" gives values for 100% escape of ^{222}Rn. "Pre-radon, total", however, includes the contribution of ^{219}Rn (because of its short half-life) and its daughters.
5. The mass abundances used in the calculations for natural uranium are (99.283±0.001)% for ^{238}U and (0.711±0.001)% ^{235}U, corresponding to the natural atomic abundances of (99.274±0.001)% and (0.720±0.001)%, respectively.
6. The activity per ppm of parent is (12.447±0.008) Bq kg^{-1} for ^{238}U, (80.030±0.056) Bq kg^{-1} for ^{235}U and (12.927±0.008) Bq kg^{-1} for natural uranium.

Table 2. Energy release and dose rates in the ^{232}Th decay series.

Isotope	Half-life (s)	σ	Alpha				Beta				Gamma			
			Energy	σ	Dose rate	σ	Energy	σ	Dose rate	σ	Energy	σ	Dose rate	σ
^{232}Th	4.43E+17	1.89E+15	3.997	0.0732	0.0820	0.0015	0.0104	0.0004	0.0002	0.0000	0.0011	0.0001	0.0000	0.0000
^{228}Ra	1.81E+08	1.89E+15					0.0091	0.0007	0.0002	0.0000	0.0004	0.0000	0.0000	0.0000
^{228}Ac	2.21E+04	1.89E+15					0.4122	0.0452	0.0085	0.0009	0.8614	0.0056	0.0177	0.0001
^{228}Th	6.03E+07	1.89E+15	5.404	0.0801	0.1109	0.0017	0.0179	0.0002	0.0004	0.0000	0.0078	0.0003	0.0002	0.0000
^{224}Ra	3.14E+05	1.99E+02	5.673	0.0039	0.1164	0.0005	0.0022	0.0000	0.0000	0.0000	0.0104	0.0001	0.0002	0.0000
^{220}Rn	5.56E+01	1.00E-01	6.287	0.0015	0.1290	0.0006					0.0006	0.0001	0.0000	0.0000
^{216}Po	1.45E-01	2.00E-03	6.778	0.0005	0.1391	0.0006					0.0000	0.0000	0.0000	0.0000
^{212}Pb	3.83E+04	3.60E+01					0.1714	0.0032	0.0035	0.0001	0.1438	0.0013	0.0029	0.0000
^{212}Bi	3.63E+03	3.60E+00	2.176	0.0054	0.0446	0.0002	0.5035	0.0013	0.0103	0.0001	0.1040	0.0012	0.0021	0.0000
^{212}Po	2.99E-07	2.00E-09	5.628	0.0053	0.1155	0.0005								
^{208}Tl	1.83E+02	2.40E-01					0.2141	0.0020	0.0044	0.0000	1.2150	0.0022	0.0249	0.0001
^{232}Th, total			35.943	0.1088	0.7375	0.0026	1.3409	0.0453	0.0275	0.0009	2.3444	0.0062	0.0481	0.0002
^{232}Th, pre-thoron			15.074	0.1085	0.3093	0.0024	0.4518	0.0452	0.0093	0.0009	0.8810	0.0056	0.0181	0.0001

Notes:
Energies are given in MeV and represent the energy emitted per disintegration.
Dose-rates are given in Gy ka^{-1} per ppm of parent, assuming equilibrium in the decay chains.
Branching ratios are (64.06±0.06)% for ^{212}Po and (35.94±0.06)% for ^{208}Tl.
The rows labeled "pre-radon" give values for 100% escape of ^{220}RN.
The activity per ppm of parent is (4.058±0.017) Bq kg^{-1}.

Table 3. Dose rate data for potassium and rubidium.

		^{40}K		^{87}Rb	
		value	σ	value	σ
Natural abundance (mg g^{-1})		0.1196	0.0010	283.0	0.2
Half-life (y)		1.248E+09	3.000E+06	4.81E+10	9.00E+08
Average energy per disintegration (MeV)	Beta	0.499	0.001	0.0817	0.0007
	Gamma	0.1558	0.0026		
Specific activity (Bq kg^{-1}) for 1% nat. K and 50 ppm of nat. Rb		317.4	2.8	44.8	0.8
Dose-rate (Gy ka^{-1}) for concentrations as above	Beta	0.8011	0.0073	0.0185	0.0004
	Gamma	0.2498	0.0048		

Table 4. An overview of calculated uncertainties for the present dose-rate values, given as σ (%). The columns labelled as G (%) show percentage relative differences between the present dose-rates and those reported in the most recent update by Guérin et al. (2011).

	alpha		beta		gamma	
	σ (%)	G (%)	σ (%)	G (%)	σ (%)	G (%)
^{238}U, total	0.41	0.00	0.28	0.21	0.18	-0.73
^{238}U, pre-radon	0.96	0.00	0.35	-0.18	0.00	0.00
^{235}U, total	0.85	-1.28	2.70	0.00	0.00	9.09
U-nat., total	0.39	-0.07	0.27	0.14	0.18	1.69
U-nat., pre-radon	0.87	-0.16	0.33	-0.17	0.00	4.54
^{232}Th, total	0.35	0.00	3.27	-0.73	0.42	0.42
^{232}Th, pre-radon	0.78	0.00	9.68	-1.08	0.55	0.55
^{40}K	-	-	0.91	0.36	1.9	0.28
^{87}Rb	-	-	2.16	0.00	-	-

Table 5. Literature comparison of uranium (^{238}U and ^{235}U) dose-rates.

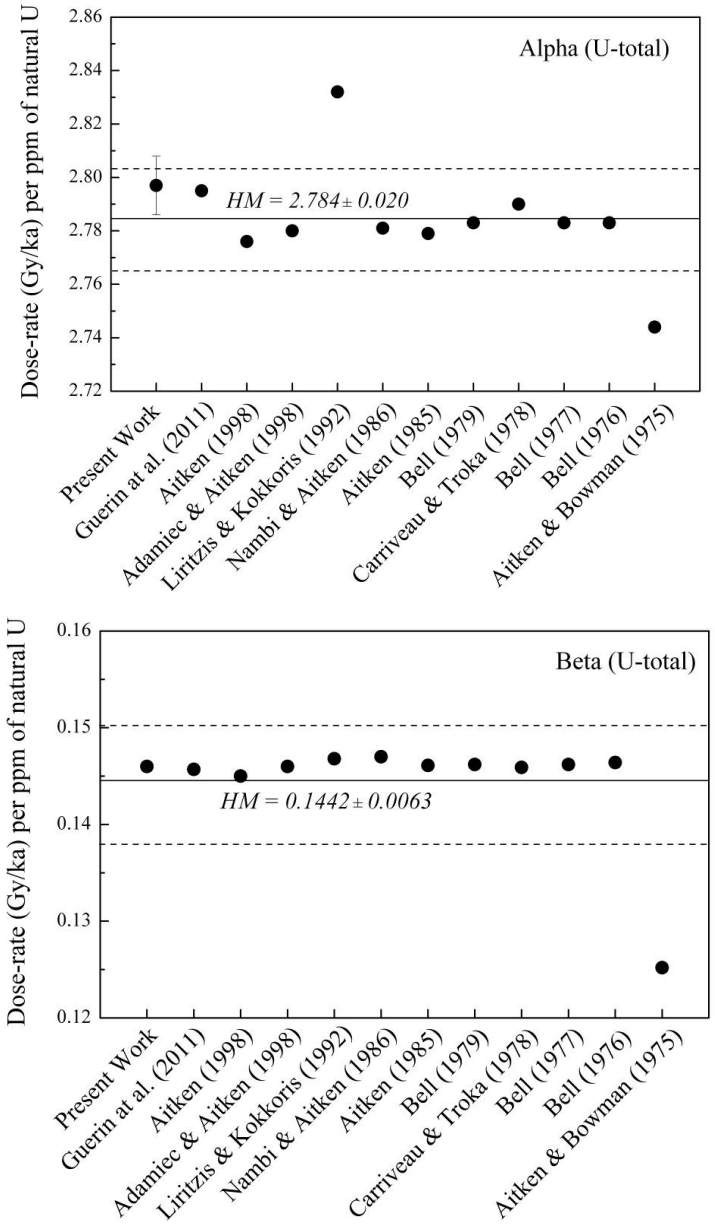
	Dose-rates (Gy ka^{-1}) per ppm of natural U											
	U, total						U, pre-radon					
Reference	Alpha	1σ	Beta	1σ	Gamma	1σ	Alpha	1σ	Beta	1σ	Gamma	1σ
Present work	2.793	0.011	0.1459	0.0004	0.1118	0.0002	1.265	0.011	0.0602	0.0002	0.0044	0.0000
Guérin *et al.* (2011)	2.795		0.1457		0.1116		1.267		0.0603		0.0042	
Aitken (1998)	2.776		0.1450		0.1130		1.106		0.0600		0.0043	
Adamiec & Aitken (1998)	2.780		0.1460		0.1130		1.260		0.0600		0.0044	
Liritzis & Kokkoris (1992)	2.832		0.1468		0.1108							
Nambi and Aitken (1986)	2.781		0.1470		0.1136		1.261		0.0613		0.0042	
Aitken (1985)	2.779		0.1461		0.1149		1.260		0.0610		0.0056	
Bell (1979)	2.783		0.1462		0.1148		1.262		0.0609		0.0056	
Carriveau & Troka (1978)	2.790		0.1459		0.1238							
Bell (1977)	2.783		0.1462		0.1148		1.262		0.0609		0.0056	
Bell (1976)	2.783		0.1464		0.1268		1.262		0.0593		0.0069	
Aitken & Bowman (1975)	2.744		0.1252		0.1197		1.257		0.0568		0.0088	
Historical Mean ± 1σ	2.784	0.020	0.1442	0.0063	0.1161	0.0051	1.244	0.052	0.0601	0.0014	0.0055	0.0015

Table 6. Literature comparison of thorium dose-rates.

	Dose-rates (Gy ka^{-1}) per ppm of ^{232}Th											
	Thorium, total						Thorium, pre-thoron					
Reference	Alpha	1σ	Beta	1σ	Gamma	1σ	Alpha	1σ	Beta	1σ	Gamma	1σ
Present work	0.7375	0.0026	0.0275	0.0009	0.0481	0.0002	0.3093	0.0024	0.0093	0.0009	0.0181	0.0001
Guérin *et al.* (2011)	0.7375		0.0277		0.0479		0.3093		0.0094		0.0180	
Adamiec & Aitken (1998)	0.7320		0.0273		0.0476		0.3050		0.0091		0.0178	
Aitken (1998)	0.7328		0.0273		0.0478		0.2708		0.0091		0.0180	
Liritzis & Kokkoris (1992)	0.7309		0.0274		0.0278							
Nambi & Aitken (1986)	0.7390		0.0286		0.0521		0.3100		0.0108		0.0203	
Aitken (1985)	0.7387		0.0286		0.0514		0.3086		0.0103		0.0208	
Bell (1979)	0.7380		0.0286		0.0514		0.3090		0.0103		0.0208	
Carriveau & Troka (1978)	0.7385		0.0275		0.0463							
Bell (1977)	0.7380		0.0286		0.0514		0.3090		0.0103		0.0208	
Bell (1976)	0.7400		0.0290		0.0500		0.3100		0.0105		0.0183	
Aitken & Bowman (1975)	0.7321		0.0241		0.0504		0.3054		0.0088		0.0186	
Historical Mean ± 1σ	0.7361	0.0034	0.0277	0.0014	0.0476	0.0069	0.3041	0.0126	0.0098	0.0007	0.0193	0.0014

Table 7. Literature comparison of potassium and rubidium dose-rates.

	Dose-rates (Gy ka^{-1}) per 1% natural K				Dose-rates (Gy ka^{-1}) per 50 ppm Rb	
Reference	Beta	1σ	Gamma	1σ	Beta	1σ
Present work	0.8011	0.0073	0.2498	0.0048	0.0185	0.0004
Guérin et al. (2011)	0.7982		0.2491		0.0185	
Adamiec & Aitken (1998)	0.782		0.243		0.019	
Liritzis & Kokkoris (1992)	0.8221		0.2460		0.025	
Nambi & Aitken (1986)	0.8144		0.2433		0.023	
Bell (1979)	0.8304		0.2492		0.025	
Carriveau & Troka (1978)	0.8023		0.2482		0.019	
Bell (1977)	0.8216		0.2470			
Aitken & Bowman (1975)	0.8650		0.2409			
Historical Mean ± 1σ	0.817	0.025	0.246	0.003	0.022	0.003



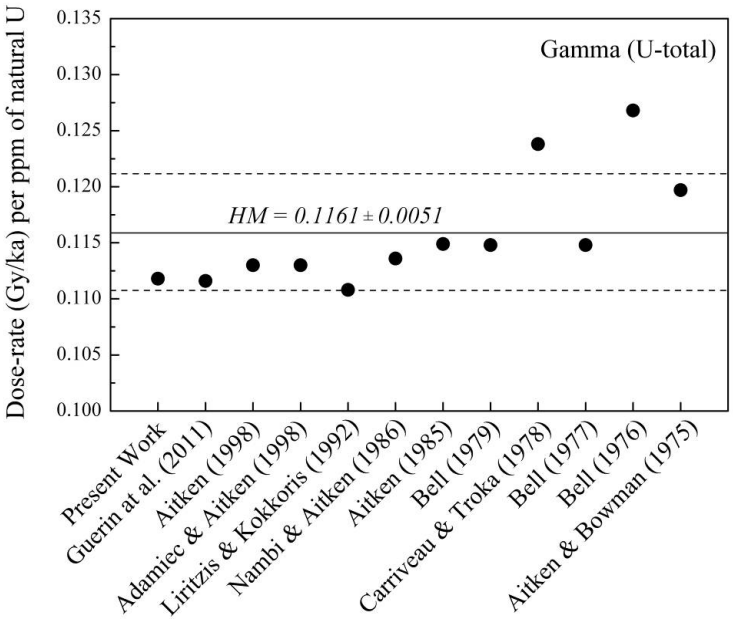


Figure 1. Literature comparison of alpha, beta and gamma dose-rates for natural U-total. The Historical Mean (*HM*) value and the corresponding ±1σ region are also indicated with the solid and dashed lines, respectively.

Table 8. Comparison of calculated individual and total dose-rates (Gy ka^{-1}) for a hypothetical sample (see the text for details), based on different dose-rate conversion factors from the present work and the literature. The calculated individual and total dose-rates based on the Historical Mean values are presented in the last row.

	Total nat. U		^{232}Th		^{40}K		^{87}Rb		Total	
	Dose-rate	σ	Dose-rate	σ	Dose-rate	σ	Dose-rate	σ	Dose-rate	σ
Present work	0.439	0.003	0.745	0.009	1.0509	0.014	0.0185	0.010	2.253	0.019
Guérin et al. (2011)	0.438		0.745		1.0473		0.0185		2.249	
Aitken (1998)	0.439		0.738		1.063		0.022		2.262	
Adamiec & Aitken (1998)	0.441		0.740		1.025		0.019		2.225	
Liritzis & Kokkoris (1992)	0.438		0.544		1.0681		0.025		2.076	
Nambi and Aitken (1986)	0.444		0.795		1.0577		0.023		2.320	
Aitken (1985)	0.444		0.789		1.063		0.022		2.318	
Bell (1979)	0.444		0.789		1.0796		0.025		2.337	
Carriveau & Troka (1978)	0.459		0.727		1.0505		0.019		2.256	
Bell (1977)	0.444		0.789		1.0686		0.022		2.323	
Bell (1976)	0.465		0.779		1.063		0.022		2.329	
Aitken & Bowman (1975)	0.417		0.734		1.1059		0.022		2.279	
Historical Mean ± 1σ	0.443	0.014	0.742	0.069	1.063	0.027	0.022	0.002	2.270	0.077

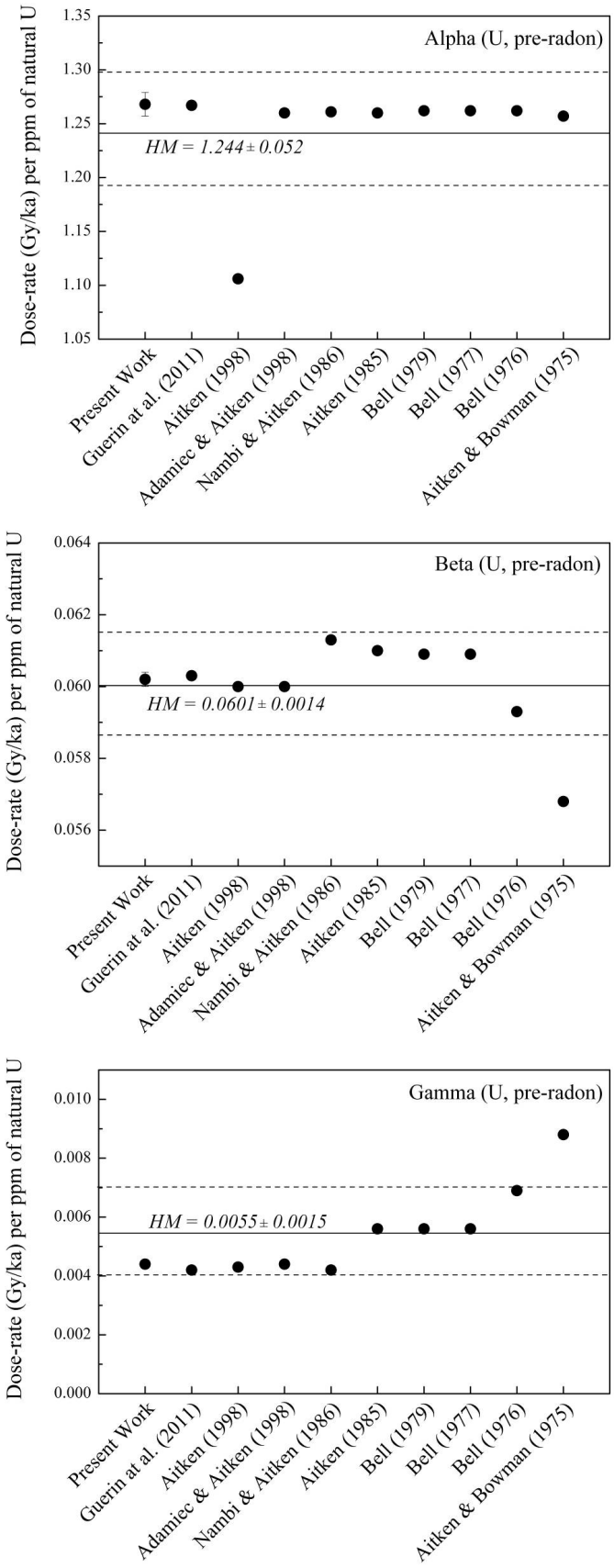


Figure 2. Literature comparison of alpha, beta and gamma dose-rates for natural U-pre-radon. The Historical Mean (*HM*) value and the corresponding ±1σ region are also indicated with the solid and dashed lines, respectively.

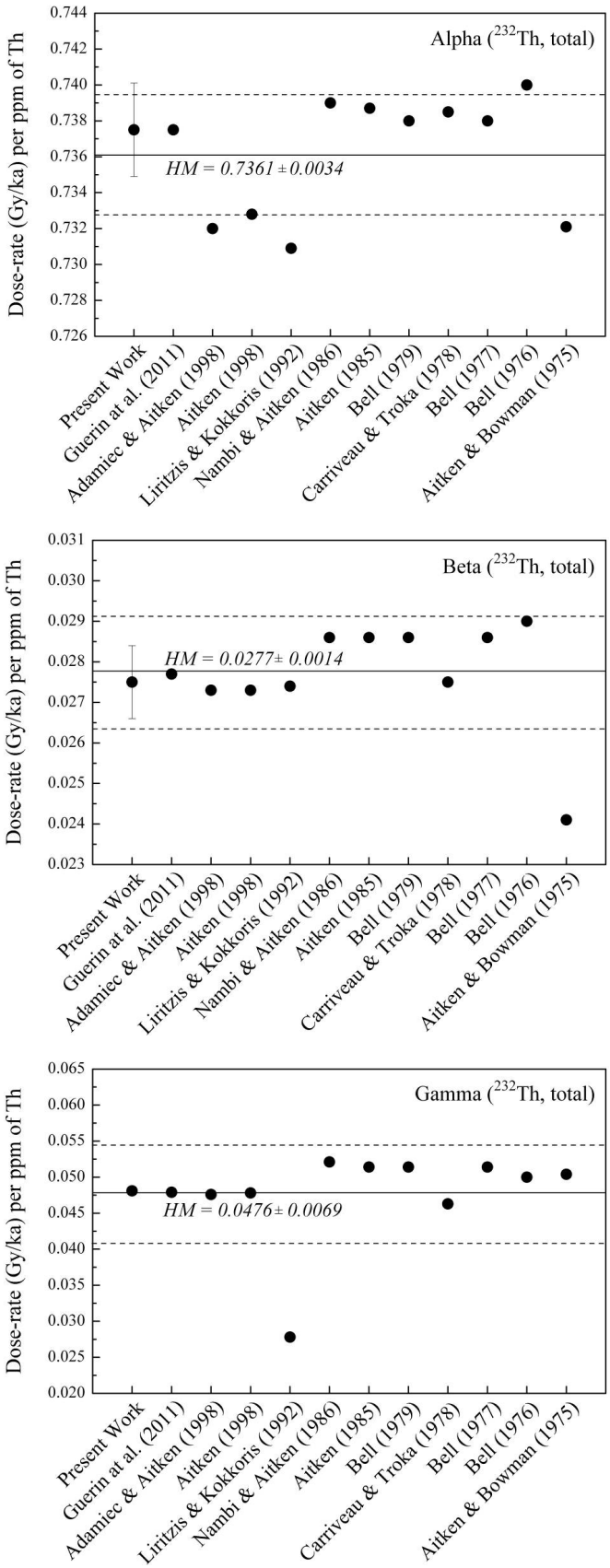


Figure 3. Literature comparison of alpha, beta and gamma dose-rates for ^{232}Th-total. The Historical Mean (*HM*) value and the corresponding ±1σ region are also indicated with the solid and dashed lines, respectively.

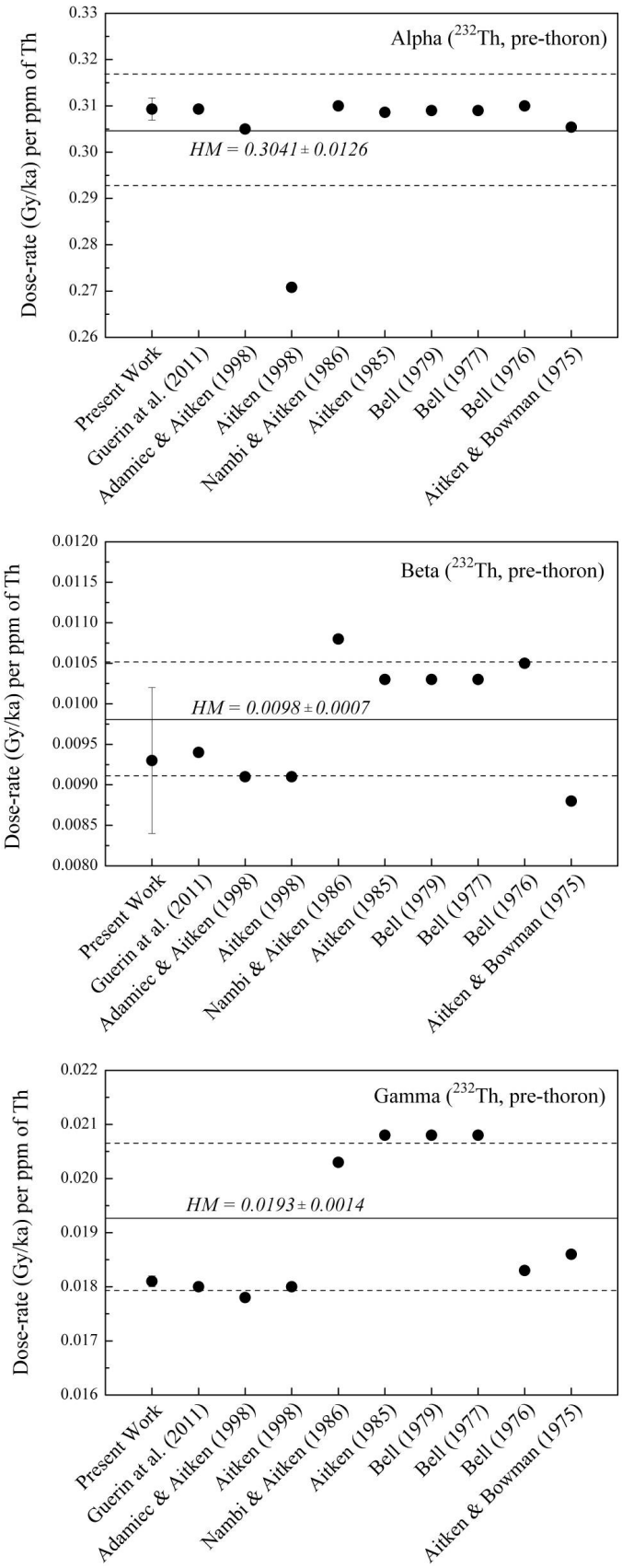


Figure 4. Literature comparison of alpha, beta and gamma dose-rates for ^{232}Th-pre-radon. The Historical Mean (*HM*) value and the corresponding ±1σ region are also indicated with the solid and dashed lines, respectively.

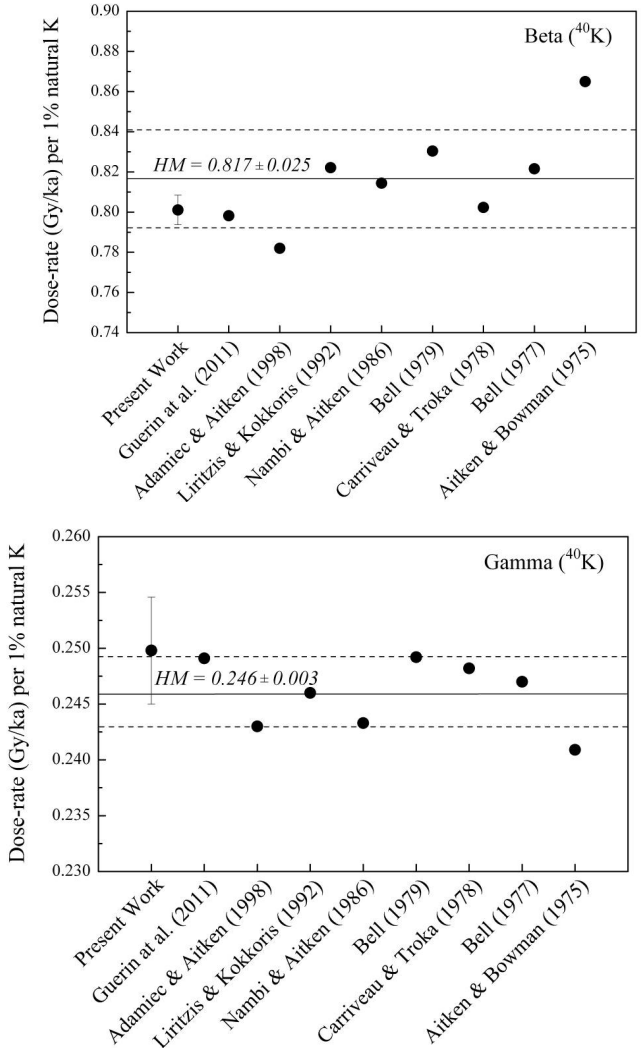


Figure 5. Literature comparison of dose-rates for ^{40}K. The Historical Mean (*HM*) value and the corresponding ±1σ region are also indicated with the solid and dashed lines, respectively.

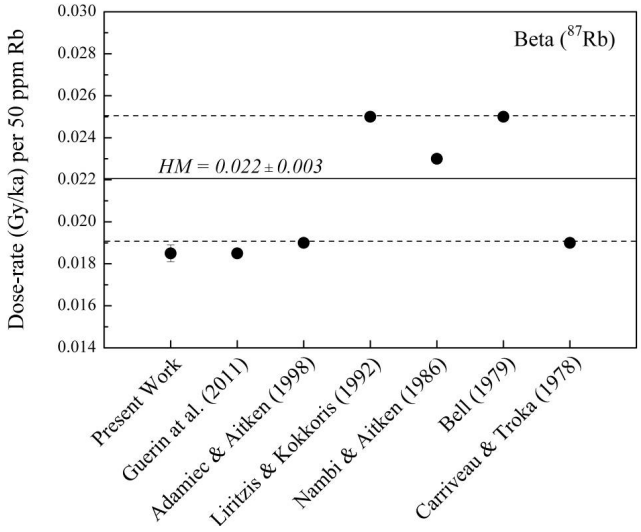


Figure 6. Literature comparison of dose-rates for ^{87}Rb. The Historical Mean (*HM*) value and the corresponding ±1σ region are also indicated with the solid and dashed lines, respectively.

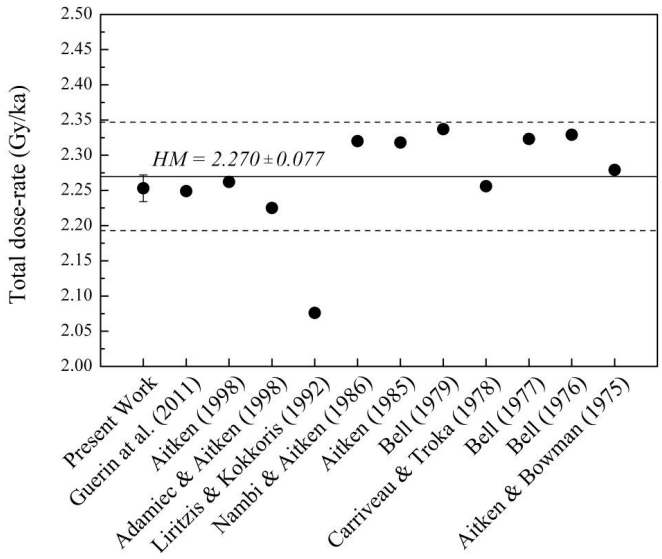


Figure 7. Comparison of total dose-rates for a hypothetical sample (see text for details), calculated using different dose-rate conversion factors, available in the literature. Calculations based on the Historical Mean (*HM*) values are also shown with the solid line. The dashed lines indicate the ±1σ region from the *HM*.