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An overview of radiological hazards related to geological external gamma radiation in outdoor environments

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Natural geologic bodies (rocks and derived soils or sediments), as well as building materials prepared from them, can constitute an important source of ionizing radiation, mainly due to the presence of uranium, thorium and potassium radionuclides in their minerals.

Highest amounts of radioisotopes, namely uranium and thorium, can be found in geologic terrains like monazite or zircon rich sedimentary bodies, organic-rich schists, carbonatites and granites (especially when affected by uranium enrichment related to alteration).

Studies on the possible health effects of such radiation have been mostly dedicated to assessing radiation doses in indoor environments both in terms of Rn concentrations and external gamma radiation (especially in relation to building materials).

The possible impact of outdoor gamma radiation has deserved less legal attention but there are several scientific publications dedicated to radioisotopes analyses and gamma dose calculations as well as some with direct gamma radiation measurements.

The **absorbed dose rate** of gamma radiation (**nGy/h**) can be assessed by different methods:

- Directly from field gamma-ray spectrometry measurements with low precision.
- From the radionuclide concentrations (or specific activities, in **Bq/kg**) in a given object obtained from laboratory analyses and converted in absorbed dose rate using factors that are varied according to the amount of the object and the distance to the object.
- Diverse factors have been proposed and here will be considered the factors listed in Markkanen 1995.

The final impact on humans (effective dose) needs also to consider:

- conversion factor (usually 0.7) from absorbed dose rate to effective dose (in mSv),
- time that humans of exposure to radiation source.

An extensive collection is presented in a document from the United Nations (UNSCEAR) which presents ranges from different countries as well as values for highly radioactive areas.
This data set has been used to explore the implications of those values in terms of the exposure time necessary for attaining a certain yearly effective dose.

Relation with radioisotope contents will also be discussed through the consideration of the gamma or concentration activity index. The version considered here will be the same of the 2013/59/EURATOM from the Council of the European Union:

$$I = \frac{C(\text{Ra-226})}{300} + \frac{C(\text{Th-232})}{200} + \frac{C(\text{K-40})}{3000}$$

The term outdoor is being used here with a very broad meaning, including spaces of the built environment that can be very different from the non-human designed terrain, such as piles of materials or the presence of pavements and façades (for which will be considered the factors presented in Markkanen).

Data treatment

Diverse statistics analyses were performed with Statistica 11 (Statsoft) and PAST.

PAST:

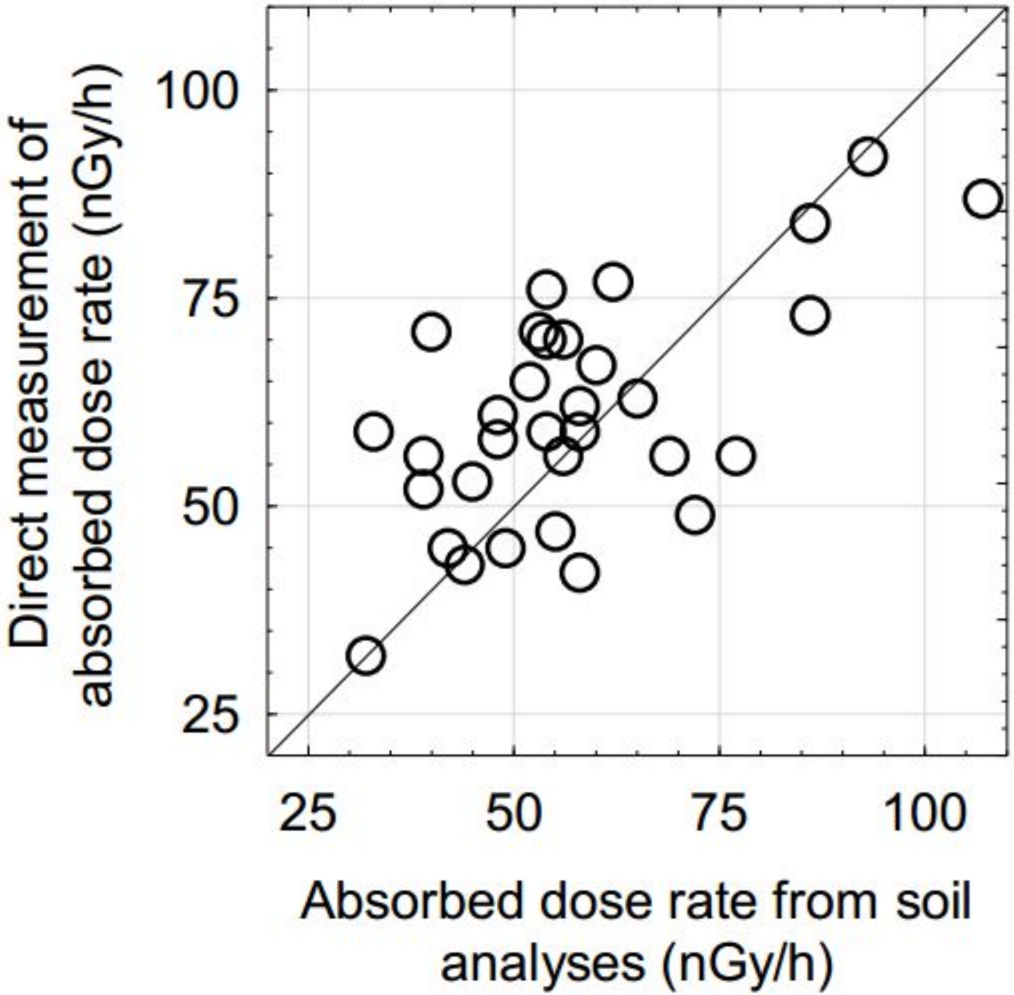
- Wilcoxon non-parametric test of comparison of the median
- Diverse statistical tests

Statistica:

- Assessment of the fit to the normal distribution by normal probability plots
- Correlation indicators (coefficient of determination, Pearson and Spearman correlation coefficients)
- All the plots

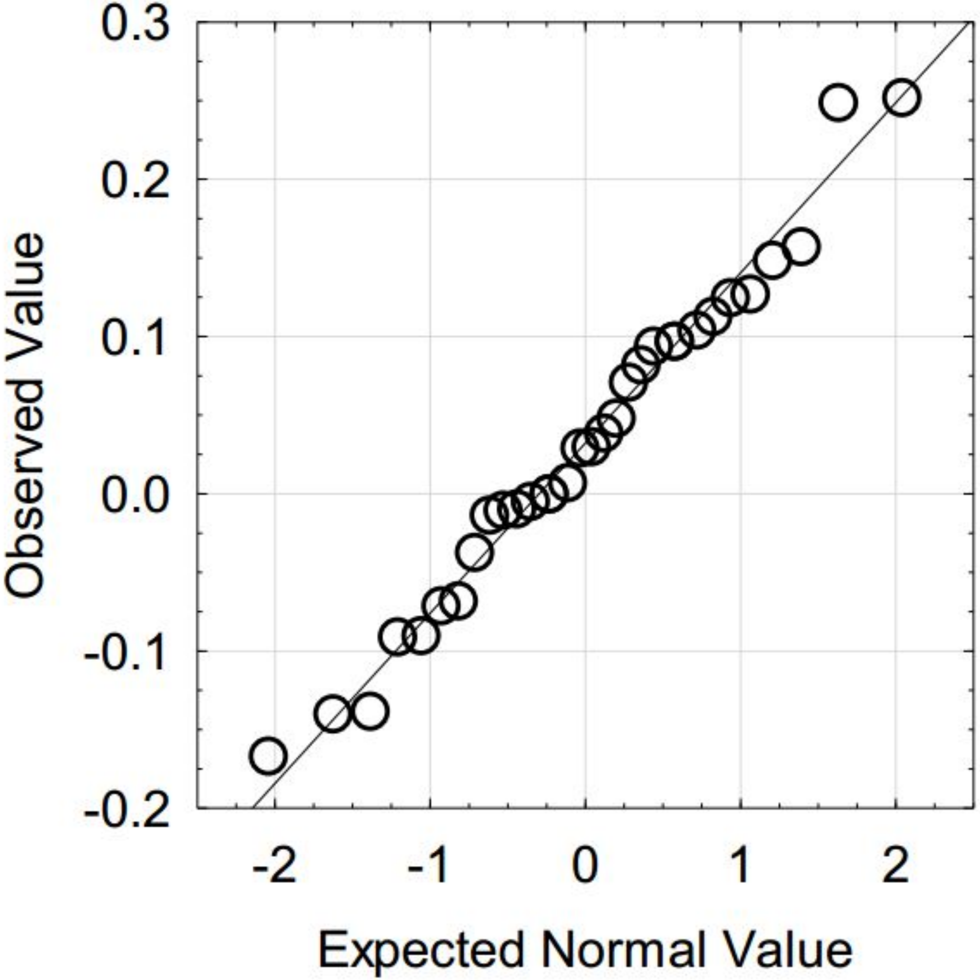
Absorbed dose rates can be measured directly or estimated from analyses of radioisotope concentrations using factors that assume a given geometrical model.

UNSCEAR presents comparative data of direct measurements and estimations from terrain analyses for the outdoors and the model of a substrate with infinite size.



Direct measurement of absorbed dose rate (nGy/h)
100
75
50
25
25
50
75
100
Absorbed dose rate from soil analyses (nGy/h)

Normal probability plot of logarithms of the ratio between values by direct measurement and values estimated from radioisotope analyses

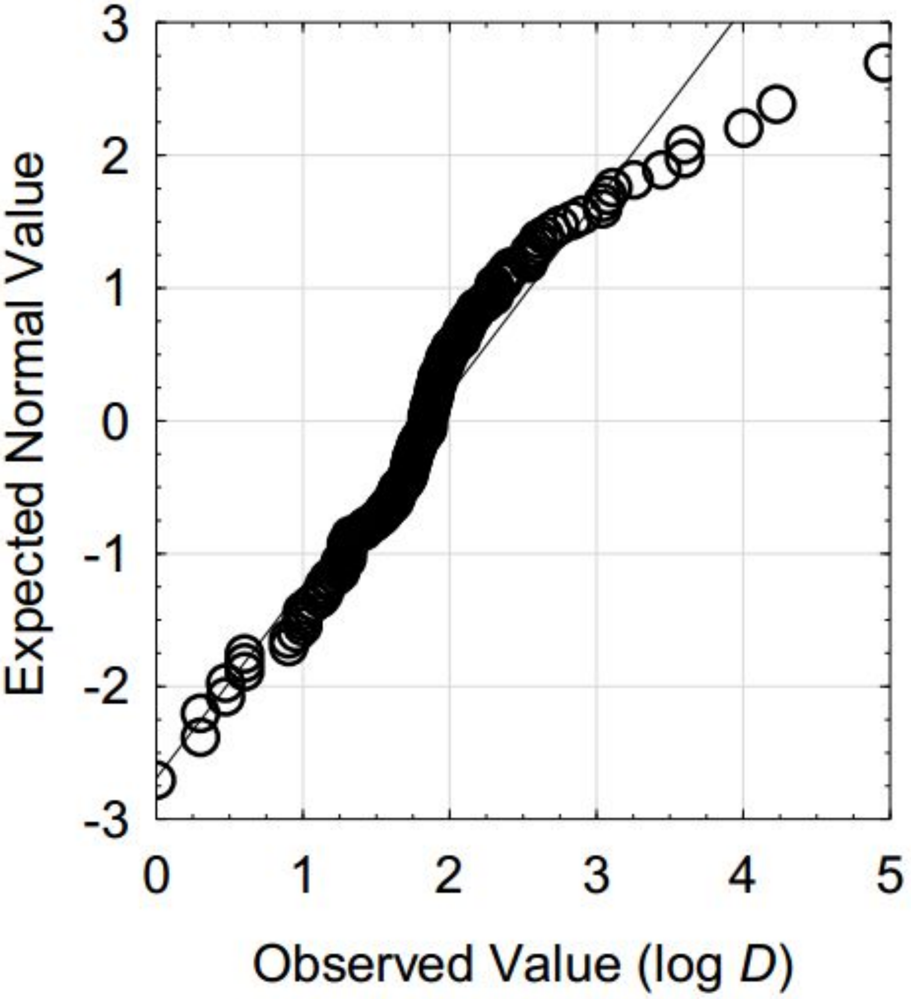


Results (*p*-values) of normality tests performed on the set of logarithms of values for several countries presented in for the ratio between direct measurements of absorbed dose rates and their estimations from radioisotope analyses. Monte Carlo *p*-values for 10^5 permutations.

Test	Shapiro-Wilk W	Anderson-Darling A	Jarque-Bera JB
p-value (normal)	0.76	0.83	0.90
p-value (Monte Carlo)	-	0.83	0.90

A statistical sample of values of absorbed dose rates was prepared from minimum, average and maximum values for different countries presented in UNSCEAR 2000 as well as the values indicated in that publication for high radioactivity areas.

The consideration of the logarithm of absorbed dose rate values shows a distribution more close to the normal distribution (corresponding to a lognormal distribution) and the mean of log-values (which corresponds to the geometric mean) is slightly higher than the median (1.86 and 1.85, respectively).



Expected Normal Value
Observed Value (log D)
3
2
1
0
-1
-2
-3
0
1
2
3
4
5

However, even for the log-values set, the diverse normality tests performed gave very low *p*-values, the set shows a pseudo-standard deviation (0.39) that is lower than the standard deviation (0.66)

This result indicates heavier than normal tails and a positive skewness (indicating the influence of the higher values, as is visible in the normal probability plot).

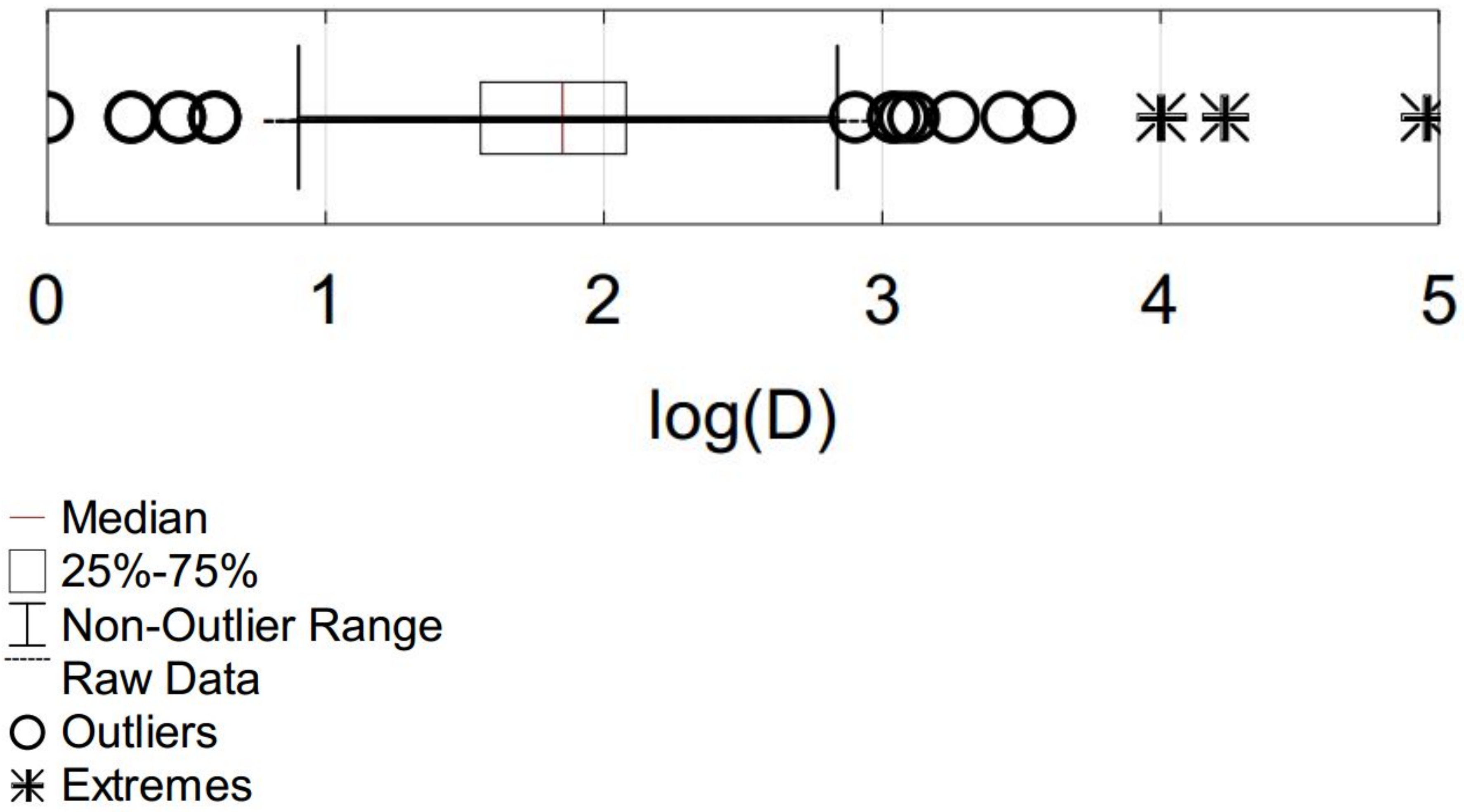
These characteristics suggest that the studied set of values can be considered conservative in terms of assessing the radiological hazards.

Normality tests (*p*-values) for the logarithms of the set of absorbed dose rate values from [1] and their estimations from radioisotope analyses. Monte Carlo *p*-values for 10^5 permutations

Test	Shapiro-Wilk W	Anderson-Darling A	Jarque-Bera JB
p-value (normal)	1.97E-08	8.95E-11	6.08E-30
p-value (Monte Carlo)	-	1.00E-05	3.00E-05

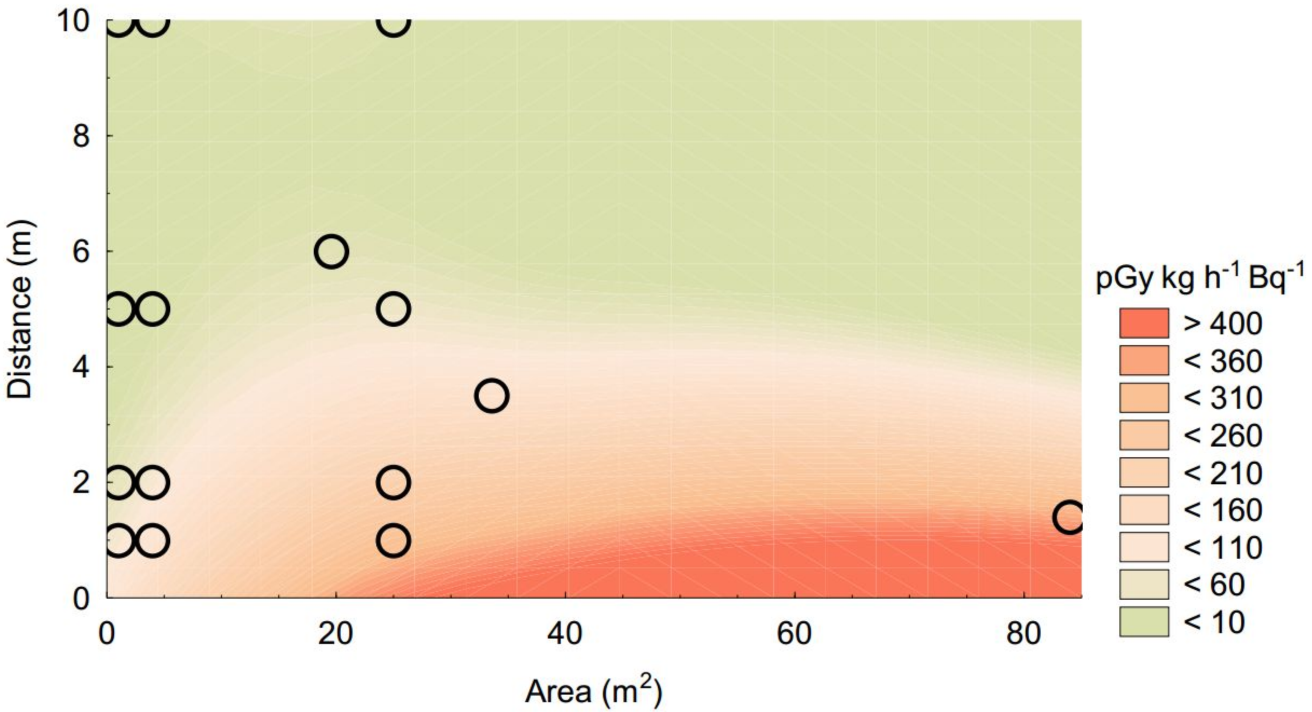
The boxplot of logarithms of absorbed dose rate is less affected by the effect of higher values, indicating as potential outliers values above around log $D = 2.5$ (corresponding to 316 nGy/h).

Given the characteristics of the distribution of values for the log-values set discussed in the previous paragraph, the consideration of the levels related to the boxplot can be considered conservative (in the sense of the assessment of radiological hazards).


0
1
2
3
4
5
log(D)
Median
25%-75%
Non-Outlier Range
Raw Data
Outliers
Extremes

Absorbed dose rates can be estimated from the radioisotope concentrations using factors that consider geometrical conditions.

A plot was prepared from diverse factors for transforming ^{226}Ra concentrations (in Bq/kg) presented in Markkanen for different situations in terms of emission area, including diverse distances (1 m, 2 m, 5 m and 10 m) from piles of material with variable facing area (1 m^2, 4 m^2 and 25 m^2), as well as factors indicated by this author for indoor walls and floors (that can also correspond to situations in the outdoors built environment as well as to outcrops with similar dimensions) for surfaces with 12.0 m x 2.8 m and a distance of 3.5 m, 7.0 m x 2.8 m and a distance of 6.0 m, 12.0 m x 7.0 m and a distance of 1.4 m.



This plot should be used with great care as the points present a very unfavourable pattern for contouring (as it can be seen from the distribution of the original points presented in the plot) but it is illustrative of the effects of the amount of material and distance.

Effective dose

The effective dose in a given period of time is obtained by multiplying the absorbed dose rate by a factor 0.7) and by the amount of time of exposure during a year.

The question of time will depend on a given exposure model. An average portion of time outdoors of 0.2 of a year (8760 hours). However, there are situations that will imply higher exposure time:

- spending a high amount of time in the outdoors, especially for workers in activities related to geologic materials extraction such as open mining or quarry and homeless people;
- Occupancy of structures made of materials with low shielding to gamma radiation.

Effective dose

The present discussion will be focused on estimating the exposure time (t) required to achieve a reference yearly effective dose (1 mSv) for a given absorbed dose rate (D) in nGy/h

$$t = 10^{(7-\log D)}/7$$

In this way, it is possible to estimate that for terrains with an absorbed dose rate corresponding to the start of the extreme outliers in the plot of Figure 3a (around 104 nGy/h) it will take around 143 hours in one year to achieve the 1 mSv value. This corresponds to around 2.75 hours per week (considering the 52 weeks) or, perhaps more worrisome, 6 hollydays living on a tent on that terrain (assuming that all the time was spent on terrain with this radiation level).

The relation with the radioisotopes composition of the terrains will depend on the geometric scenario considered.

Sanjurjo-Sanchez and Alves proposed the use of partial gamma indexes, I(U), I(Th), and I(K), calculated by dividing the radioisotopes activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K by the factors used as denominators in the activity concentration or gamma index proposed for the assessment of building materials (300 for ^{226}Ra, 200 for ^{232}Th and 3000 for ^{40}K).

For the factors proposed in Markkanen for a pile of material with an infinite facing area, the contributions of the radioisotope activity concentrations can be calculated from these partial gamma indexes by multiplying by 141, 114 and 126 (respectively for ^{226}Ra, ^{232}Th and ^{40}K).

A simple relation between the exposure time (hours in a year) to achieve the 1 mSv effective dose in a year and the activity concentration or gamma index (I):

$$10^{(7-\log I)}/(7 \times 141) \leq t \leq 10^{(7-\log I)}/(7 \times 114)$$

There is at least one potentially interesting result from this relation. Directive 2013/59/EURATOM [7] indicates the referred activity concentration index for the control of building materials and proposes as “conservative screening tool” a value of 1 for this index. A pile of material with $I = 1$ and an infinite facing area will give an absorbed dose rate that is not higher than 141 nGy/h which for 8760 hours in a year will give an effective dose of 0.86 mSv. Similar relations could be proposed for other exposure scenarios.

A worse scenario in the outdoor would be to be over a rock pavement and near a very big wall rock; assuming that one should consider the factors proposed in Markkanen for a pile of material with an infinite facing material, the factors for converting the partial gamma indexes in contributions to absorbed dose rates will be double.

Assuming an exposure of 48 hours/week and 51 weeks by year, this will imply (for the highest factor of conversion between index and dose rate) an effective dose per year of 0.48 mSv for materials with *I* equal to 1. However, for people living in this exposure situation 8760 hours per week, this will imply an effective dose of 1.7 mSv per year (for the highest factor).

There could be even worse situations, which one can consider being on the fringe of outdoor/indoor, if there are more surfaces or for people dwelling on small open cavities on rock massifs.

Conclusions

In a perspective of estimation of the time exposure necessary to achieve a reference level of 1 mSv per year of effective dose due to gamma radiation in the outdoors, this work shows that this time is directly proportional to $10^{(7-\log D)}$, with D being the absorbed dose rate (in nGy/h) or $10^{(7-\log I)}$, being I the gamma or activity concentration index. These relations allow assess radiological risks due to outdoor exposure according to diverse models of exposure.

Conclusions

However, concerning the relation with the gamma index correspond to a certain model of emission surface and other configurations of outdoor surfaces in the built environment can imply higher radiological risks.

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