Joint ICTP-IAEA Workshop on Advanced Solutions for Field Measurements (SMR 3729), 8-19 Aug 2022, Trieste (Italy)

Measurement of dose rate, calculation from gamma spectrum

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Content

- Basic principles, units
- Measurement methods
- ISO + Lemercier calculation
  - Mathematical approach
  - Geometry
  - ISO interpretation
- Conclusions and suggestion

Basic principle

Absorbed dose (D):

absorbed energy in material

Unit: Gy gray

1 Gy = 1 J / 1 kg

***Old unit:* rad**

1 rad = 0.01 gray

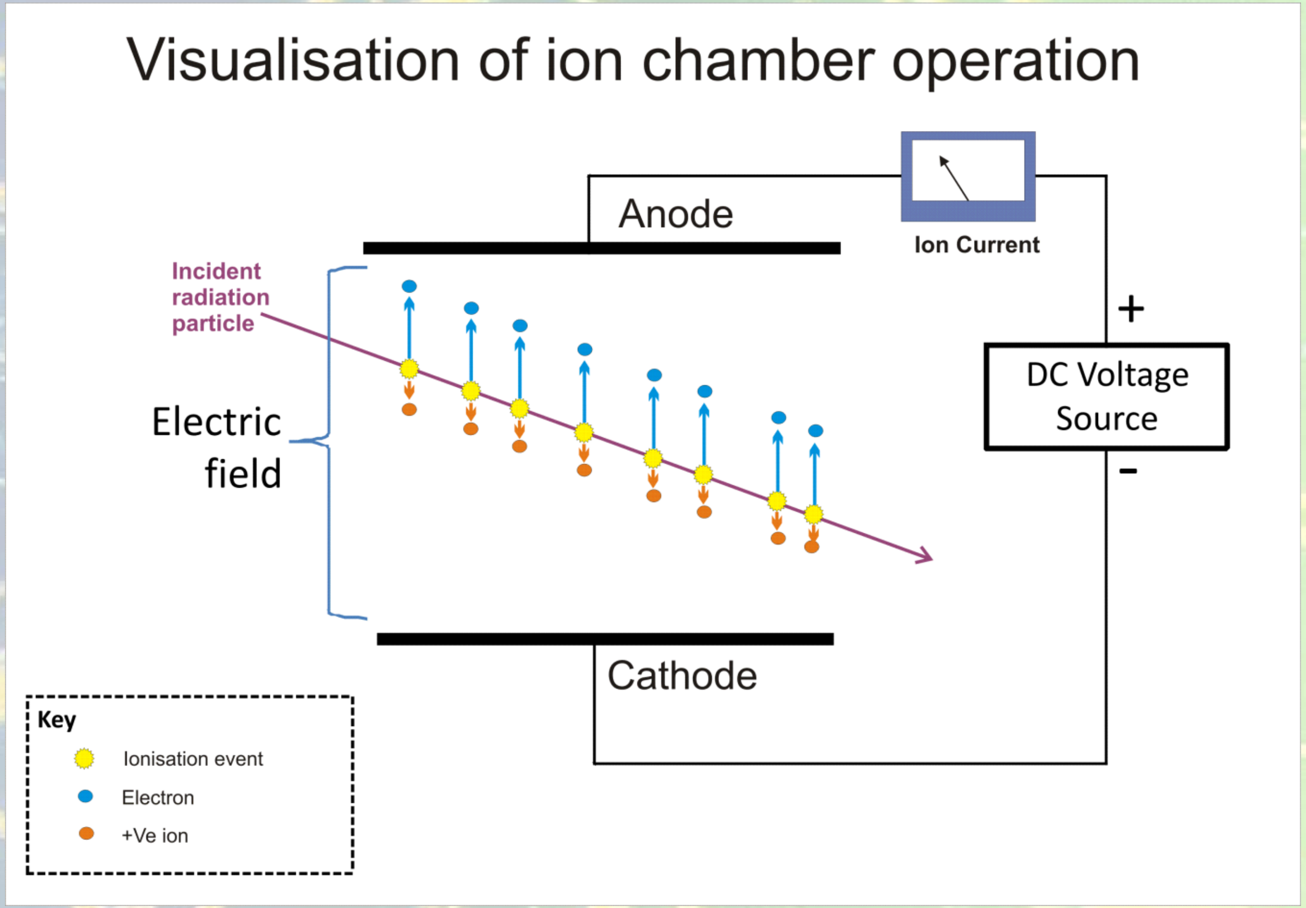
Historical definition (exposure):

Produced electric charge in dry air

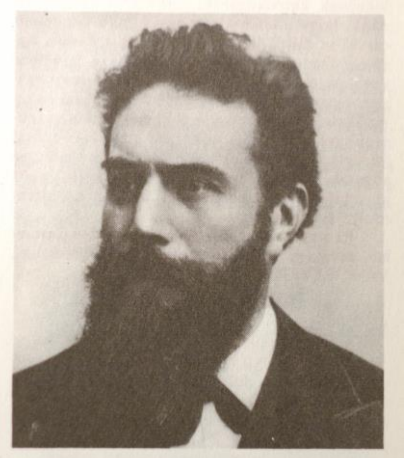
Unit: R röntgen (roentgen)

NIST definition from 1998

1 R = 2.58×10^{-4} C/kg dry air *(coulomb/kg)*



Wilhelm Conrad Röntgen
1845-1923 (1901 Nobel Prize)



Equivalent dose and effective dose (the life is not so easy)

Equivalent dose (H_T):

Considering the type of the radiation (same?) biological effect

Unit: Sv sievert

$$H_T = D \times W_R \quad J/kg$$

W_R weight factor due to the type and energy of the radiation

Effective dose (E):

In addition, considering the sensitivity of the human tissue

Unit: Sv sievert

$$E = \sum W_T \times \sum W_R \times D \quad J/kg$$

Introducing the time as additional parameter

Absorbed dose rate : Gy/h

Effective dose rate: Sv/h

The calibration of the equipments:

Absorbed dose rate (Gy/h, mGy/h, µGy/h, nGy/h)

Effective dose rate (Sv/h, mSv/h, µSv/h, nSv/h)

+ combinations

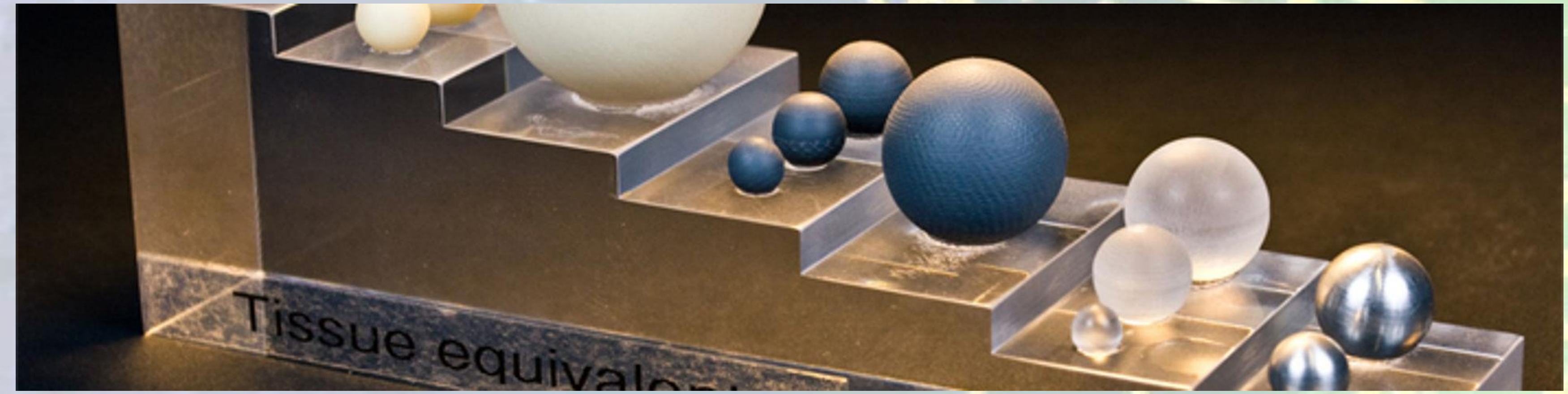
Ambient dose equivalent H(10) for area monitoring*

Directional dose equivalent H(0.07) for skin, eye lens*

ICRP 103 definition

- *"The dose equivalent at a point in a radiation field that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth of 10 mm on the radius vector opposing the direction of the aligned field."*

- ***ICRU sphere: human body tissue equivalent material (phantom)***
  - ***Diameter 30 cm***
  - ***Density 1 g/cm^3***
  - ***Composition (mass %)***
    - 76.2% Oxygen
    - 11.1 % Carbon
    - 10.1 % Hydrogen
    - 2.6 % Nitrogen



Systems for dose standardisation

- Primary standards
  - Top of the traceability chain: chemical methods (dichromate, ceric-cerous sulphate, ethanol-chlorobensene systems, calorimeters)
- Hierarchy of standard laboratories
  - Primary Standard Dosimetry Laboratory (chemical methods, calorimeters, ionisation chambers; 1%)
  - Secondary Standard Dosimetry Laboratory (calorimeters, ionisation chambers, 3%)

Calorimeter (graphite) : 710 Gy/^{0}C, required accuracy of the temperature measurement in the range of μ^{0}C

High purity water phantom calorimeter

Standard „cardinal" (not so healthy however it is tasty)

- Energy is 286 kcal = 1200 J
- **Average man 73 kg 16 J/kg ≈ 16 Gy**
- **Average lady 60 kg 20 J/kg ≈ 20 Gy**

- It seems it is more deathly for ladies

Metrological traceability of the routinely used equipment for gamma dose rate measurement

Equipment	Energy compensation	Measured parameter	Conversion to dose rate	Traceability
Ionisation chamber	Gas pressure, material of the wall	Current	Single factor	High level
Proportional detector (rate meter mode)	Filters, material of the wall	Current	Single factor	Good
Proportional detector (counter mode)	Filters, material of the wall	Counts/s	Single factor	Acceptable
GM tube	Filters, material of the wall	Counts/s	Single factor	Acceptable
Plastic scintillator (human body equivalent)		Counts/s	Single factor	Good
Plastic scintillator (human body equivalent), spectrometer mode		Energy selective counts	Mathematical model	Good
NaI(Tl) scintillator, spectrometer mode		Energy selective counts	Mathematical model	Acceptable (required a special calibration)
CZT (spectrometer mode)		Energy selective counts	Mathematical model	Acceptable (required a special calibration)

Performance criteria for dose rate monitors (metrological only)

Requirement	Essential (minimum requirements)	Desirable (it should be)
Linearity of response	Better than 30%	Better than 20%
Response time	10 s below 10 mSv/h, 2 s above 10 mSv/h	3 s below 10 mSv/h, 2 s above 10 mSv/h
Statistical fluctuations	±10% at 10 microSv/h	±5% at 10 microSv/h
Background indications	±30% fluctuations at (or less than) 1 microSv/h	±15% fluctuations at (or less than) 1 microSv/h
Overload performance	Statisfactory overload and return to normal function less than 5 min	Statisfactory overload and return to normal function less than 2 min
Photon energy response	Accross the specified energy range of the instrument the response is unity ±30%	Accross the specified energy range of the instrument the response is unity ±20%
Polar response	For angle of 180^0 in both horizontal and vertical planes, the response normalised to the reference radiation at 0^0, shall be unity ±30%	For angle of 180^0 in both horizontal and vertical planes, the response normalised to the reference radiation at 0^0, shall be unity ±20%

Performance Standards and Test Protocols for Radiological Equipment
Number 2 — Dose Rate Instrumentation
Publication No. 2B/10

Gamma dose rate measurement conditions by handheld monitors

- **Position:** 1m distance from the ground level
- **Duration:** waiting until the adjusted time constant
  - Ten independent readout
  - Result: average and rsd(%)
- **Issues:**
  - Calculating the moving average by the equipment (may be a factory adjustment)
  - High variation of readouts due to the low count rate
  - Thermic stability
  - Orientation effect (PM tube)
- **The result is the combination of the:**
  - cosmic contribution (depending on the geographical location, solar activity)
  - aerial (in normal situation ^{222}Rn progenies), usually it is negligible
  - terrestrial (from the radioactive content of the soil)

Estimating the terrestrial gamma dose rate by the Lemercier method

- **In situ gsp**: Obtain a gamma-ray spectra of the area by HPGe detector, 1 m above the soil
- **Spectra evaluation**: Determine the radionuclide content, Bq/kg or Bq/m^2
- **Spectra evaluation**: Estimate the kerma rate by isotopes, Gy
- **Dose rate estimation**: Conversion of the kerma to the H*(10) dose rate, nuclide by nuclide

First two steps: ISO 18589-7 or any other validated method

Last two steps: Lemercier estimation

In the final shape of the method the last two steps are combined.

Mathematical approach

- The activity concentration of the soil is determined using a normal in situ evaluation method up to Bq/m^2 or Bq/kg depending on the distribution of the radionuclide

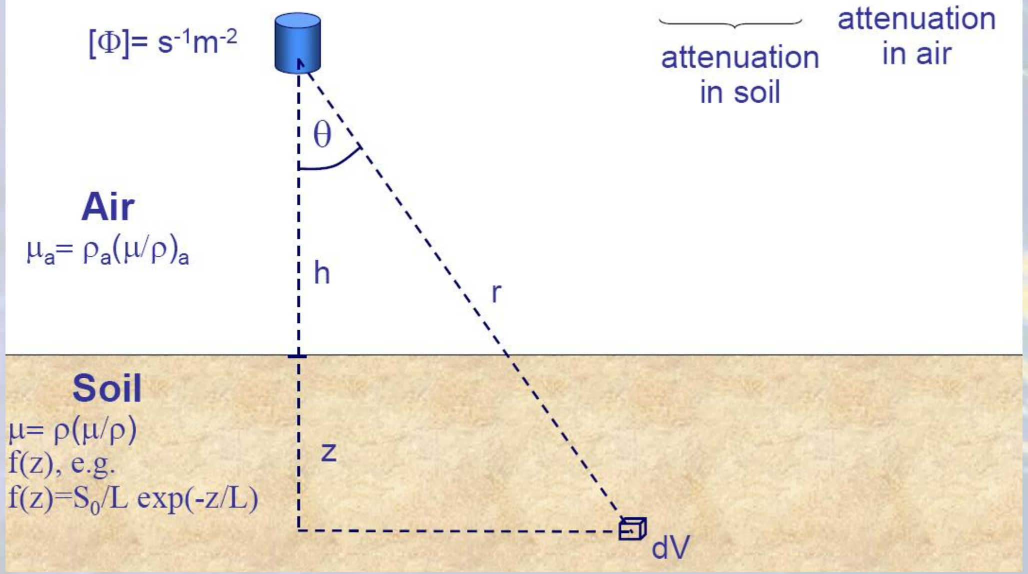
- Monte Carlo simulation to derive the flux/activity ration (Φ/A)
  - Unit is 1×10^{-4} nSv/h per Bq/m^2 (for different vertical distribution) or nSv/h per Bq/kg (for homogeneous)

- The Monte Carlo simulation has been validated by numerical calculations

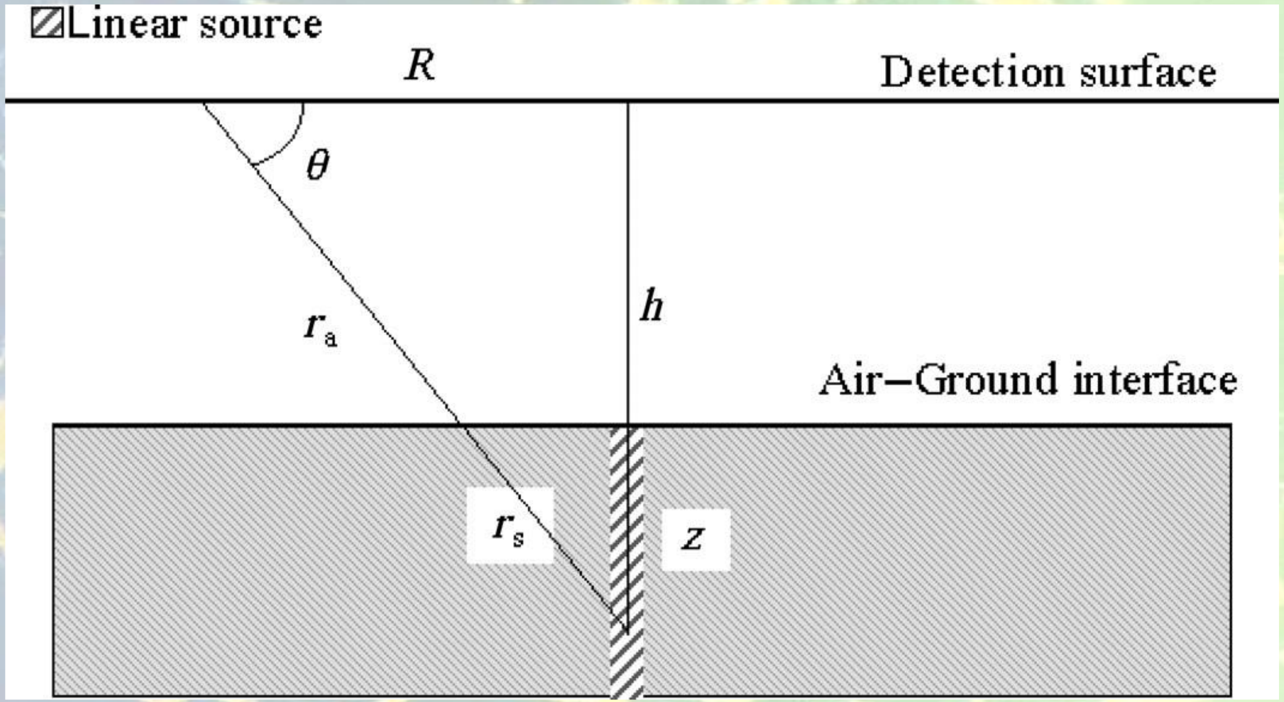
Geometry for measurement and for estimation

Measurement

$$\Phi = \int_0^{\pi/2} d\theta \int_{h/\cos\theta}^{\infty} \frac{S_0}{4\pi r^2} e^{-z/L} \cdot 2\pi r^2 \sin\theta \cdot e^{-\mu(r-h/\cos\theta)} \cdot e^{-\mu_a h/\cos\theta}\, dr$$



H*(10) dose rate estimation



(Almost opposite geometrical approach.)

$$\Phi = \rho \cdot \int_{z=0}^{z_{\max}} \int_{R=0}^{\infty} \int_{\varphi=0}^{2\pi} A_v(z) \frac{e^{-\mu_a r_a} \cdot e^{-\mu_s r_s}}{4\pi \cdot (r_a + r_s)^2} \cdot \mathrm{d}z \cdot R \cdot \mathrm{d}R \cdot \mathrm{d}\phi$$

Results for homogeneous distribution

Applicable for

- Natural radionuclides in undisturbed soil
- ^{137}Cs in cultivated soil (agricultural land)

Table 4. Specific activity to H*(10) conversion coefficients for a homogeneous distribution for the natural series in equilibrium ^{40}K, and ^{137}Cs.

	nSv h^{-1} per Bq kg^{-1}
^{232}Th family	
^{208}Tl	0.387
^{228}Ac	0.280
^{212}Pb	0.0443
^{212}Bi	0.034
^{224}Ra	0.00347
Total	0.749
^{238}U family	
^{214}Bi	0.480
^{214}Pb	0.0817
^{226}Ra	0.00228
Total	0.564
^{40}K	0.0512
^{137}Cs	0.192

Results for different relaxation length (β=0 flat, β=∞ homogeneous)

Table 3. Specific activity to H*(10) conversion coefficients (expressed in 1.10^{-4} nSv h^{-1} per Bq m^{-2} (A) and in nSv h^{-1} per Bq kg^{-1} (B)) for different source distributions.

Energy (keV)	1.10^{-4} nSv h^{-1} per Bq m^{-2}							nSv h^{-1} per Bq kg^{-1} $\beta = \infty$ (homogeneous)
	$\beta = 0$	$\beta = 0.3$	$\beta = 1$	$\beta = 5$	$\beta = 10$	$\beta = 20$	$\beta = 50$	
50	4.85	3.41	2.36	0.940	0.544	0.300	0.127	0.0066
100	6.69	5.49	4.39	2.44	1.62	0.987	0.460	0.0249
150	9.74	8.02	6.48	3.88	2.68	1.68	0.810	0.0449
200	12.8	10.7	8.57	5.19	3.66	2.31	1.14	0.0659
250	15.9	12.9	10.5	6.39	4.59	2.95	1.46	0.0854
364	22.0	18.0	14.7	9.04	6.44	4.21	2.11	0.124
500	29.2	23.6	19.3	11.8	8.56	5.62	2.85	0.170
662	36.4	30.4	24.0	15.0	10.8	7.23	3.67	0.221
750	40.7	33.6	26.4	16.6	12.0	8.04	4.13	0.252
1000	50.5	41.7	33.5	20.8	15.2	10.2	5.34	0.336
1173	57.2	47.4	38.2	23.5	17.3	11.8	6.113	0.385
1250	59.3	49.3	40.4	24.7	18.3	12.4	6.512	0.414
1333	64.4	51.9	42.7	26.1	19.2	13.2	6.921	0.441
1460	67.9	55.3	45.6	27.8	20.7	14.1	7.53	0.483
1765	77.9	64.3	52.7	33.2	24.2	16.6	8.91	0.575
2004	85.7	71.4	57.3	36.1	26.8	18.7	9.97	0.655
2250	92.5	75.8	62.5	39.6	29.6	20.5	11.1	0.733
2500	101	82.8	67.4	42.6	32.0	22.4	12.3	0.826

ISO interpretation and two scenarios based on two realistic emergency

ISO 18589-7

$$\dot{D}_{V,N} = f_D \times a$$

$$\dot{H}^*_{V,N}(10) = f_{\dot{H}^*(10)} \times a$$

$\dot{D}_{V,N}$	kerma dose rate
$\dot{H}^*_{V,N}(10)$	ambient dose equivalent rate
V	distribution model
N	radionuclide
a	activity per unit of surface or mass
f_D	kerma dose rate conversion factor for the unit of surface or mass
$f_{\dot{H}^*(10)}$	ambient dose equivalent rate conversion factor for the unit of surface or mass

f_D kerma dose rate conversion factor
$f_{\dot{H}^*(10)}$ ambient dose equivalent rate conversion factor

- Defined for the specific radionuclide.
- Defined at 1 m height above the ground surface.
- Defined for specific relaxation mass per unit area ß

- **<u>Listed in Annex G</u>**
- **f_D for homogenous distribution**
  - Uranium – Radium decay chain (equilibrium assumed)
  - Thorium decay chain (equilibrium assumed)
  - ^{40}K
- **f_D and $f_{\dot{H}^*(10)}$ for some relevant artificial radionuclides and various relaxation masses per unit area**

f_D for homogenous distribution listed in *ISO 18589-7* *

Radionuclide	Factor f_D $nGy \cdot kg \cdot h^{-1} \cdot Bq^{-1}$
Uranium / Radium series	
^{238}U	$4{,}33 \cdot 10^{-5}$
^{234}U	$5{,}14 \cdot 10^{-5}$
^{234}Th	$9{,}47 \cdot 10^{-4}$
^{234m}Pa	$3{,}00 \cdot 10^{-3}$
^{234}Pa	$4{,}49 \cdot 10^{-4}$
^{230}Th	$6{,}90 \cdot 10^{-5}$
^{226}Ra	1,2[illegible] [bez názvu] 0−3
^{222}Rn	$8{,}78 \cdot 10^{-5}$
^{214}Pb	$5{,}46 \cdot 10^{-2}$
^{214}Bi	$4{,}01 \cdot 10^{-1}$
^{210}Tl	$1{,}15 \cdot 10^{-4}$
^{210}Pb	$2{,}07 \cdot 10^{-4}$
Uranium series, total	$4{,}62 \cdot 10^{-1}$

Radionuclide	Factor f_D $nGy \cdot kg \cdot h^{-1} \cdot Bq^{-1}$
Thorium series	
^{232}Th	$4{,}78 \cdot 10^{-5}$
^{228}Ra	$5{,}45 \cdot 10^{-5}$
^{228}Ac	$2{,}21 \cdot 10^{-1}$
^{228}Th	$3{,}44 \cdot 10^{-4}$
^{224}Ra	$2{,}14 \cdot 10^{-3}$
^{220}Rn	$1{,}73 \cdot 10^{-4}$
^{212}Pb	$2{,}77 \cdot 10^{-2}$
^{212}Bi	$2{,}72 \cdot 10^{-2}$
^{208}Tl	$3{,}26 \cdot 10^{-1}$
Thorium series, total	$6{,}04 \cdot 10^{-1}$
^{40}K	$4{,}17 \cdot 10^{-2}$

** ICRU-Report 53, Gamma-Ray Spectrometry in the Environment, International Commission on Radiation Units and Measurements, 1994*

f_D for some relevant artificial radionuclides and various relaxation masses per unit area listed in *ISO 18589-7* [1*]

- ***ß = 0, 1, 3, 5, 10, 20, 50, 100***
- 44 nuclides

$f_{\dot{H}^*(10)}$ for some relevant artificial radionuclides and various relaxation masses per unit area listed in *ISO 18589-7* [2*]

- ***ß = 0, 3, 10, 50, 100, 200, 500***
- Uranium – Radium decay chain
- Thorium decay chain
- and 22 nuclides

[1] ICRU-Report 53, Gamma-Ray Spectrometry in the Environment, International Commission on Radiation Units and Measurements, 1994*

[2] Commission fédérale de Protection contre les radiations et de surveillance de la Radioactivité Recommendation concerning the use of the factor h*(10) by measuring of ambient dose equivalent rate H*(10) with situ gamma spectrometry. Secrétariat scientifique KSR/CPR, Office fédéral de la santé publique, 3003 Bern, 25 janvier 2010*

f_D for fresh fission products and fresh fallout (ß = 0)

Nuclide	f_D [nGy m^2 h^{-1} Bq^{-1}]
Nb-95	$3{,}35 \cdot 10^{-3}$
Zr-95	$3{,}23 \cdot 10^{-3}$
Mo-99	$6{,}54 \cdot 10^{-4}$
Tc-99m	$5{,}66 \cdot 10^{-4}$
Ru-103	$2{,}21 \cdot 10^{-3}$
Rh-106	$9{,}30 \cdot 10^{-4}$
I-131	$1{,}74 \cdot 10^{-3}$
Te-132	$1{,}29 \cdot 10^{-3}$
I-132	$9{,}88 \cdot 10^{-3}$
I-133	$2{,}72 \cdot 10^{-3}$
Cs-137	$2{,}68 \cdot 10^{-3}$
Ba-140	$9{,}32 \cdot 10^{-4}$
La-140	$9{,}27 \cdot 10^{-3}$
Ce-141	$3{,}67 \cdot 10^{-4}$
Ce-143	$1{,}39 \cdot 10^{-3}$
Ce-144	$1{,}08 \cdot 10^{-4}$

f_D for primary coolant and fresh fallout (ß = 0)

Nuclide	f_D [nGy m² h⁻¹ Bq⁻¹]	Nuclide	f_D [nGy m² h⁻¹ Bq⁻¹]
Be-7	$2,26 \cdot 10^{-4}$	I-132	$9,88 \cdot 10^{-3}$
K-40	$4,17 \cdot 10^{-2}$	Te-132	$1,29 \cdot 10^{-3}$
Co-58	$4,38 \cdot 10^{-3}$	I-133	$2,72 \cdot 10^{-3}$
Co-60	$1,02 \cdot 10^{-2}$	Cs-134	$6,85 \cdot 10^{-3}$
Nb-95	$3,35 \cdot 10^{-3}$	Cs-136	$9,08 \cdot 10^{-3}$
Zr-95	$3,23 \cdot 10^{-3}$	Cs-137	$2,68 \cdot 10^{-3}$
Mo-99	$6,54 \cdot 10^{-4}$	Ba-140	$9,32 \cdot 10^{-4}$
Tc-99m	$5,66 \cdot 10^{-4}$	La-140	$9,27 \cdot 10^{-3}$
Ru-103	$2,21 \cdot 10^{-3}$	Ce-141	$3,67 \cdot 10^{-4}$
Ag-110m	$1,18 \cdot 10^{-2}$	Ce-143	$1,39 \cdot 10^{-3}$
Sb-124	$7,58 \cdot 10^{-3}$	Ce-144	$1,08 \cdot 10^{-4}$
I-131	$1,74 \cdot 10^{-3}$		

Balance of the method

Advantage

- It gives a nuclide specific information for the H*(10)
- Easy calculation from the final tables, it can be adopted into the libraries of the gamma ray evaluation software
- The kerma from the scattered photons is considered
- The method covers a wide energy range 50-2500 keV
- Homogeneous, flat and realistic vertical distributions have been evaluated

To be considered

- The physical property of the soil plays a serious role two times
- The limits for the Monte Carlo simulation are too wides for air 1500 m radius and 500 m height, for soil 1500 m radius and 1.5 m height comparing the capability of the in situ gamma-ray spectrometry.
  Most of the calibration covers 40 m circle and 20 cm depth
- Validated by numerical calculation (most probably both calculation way are using the same response functions)

Disturbing effects

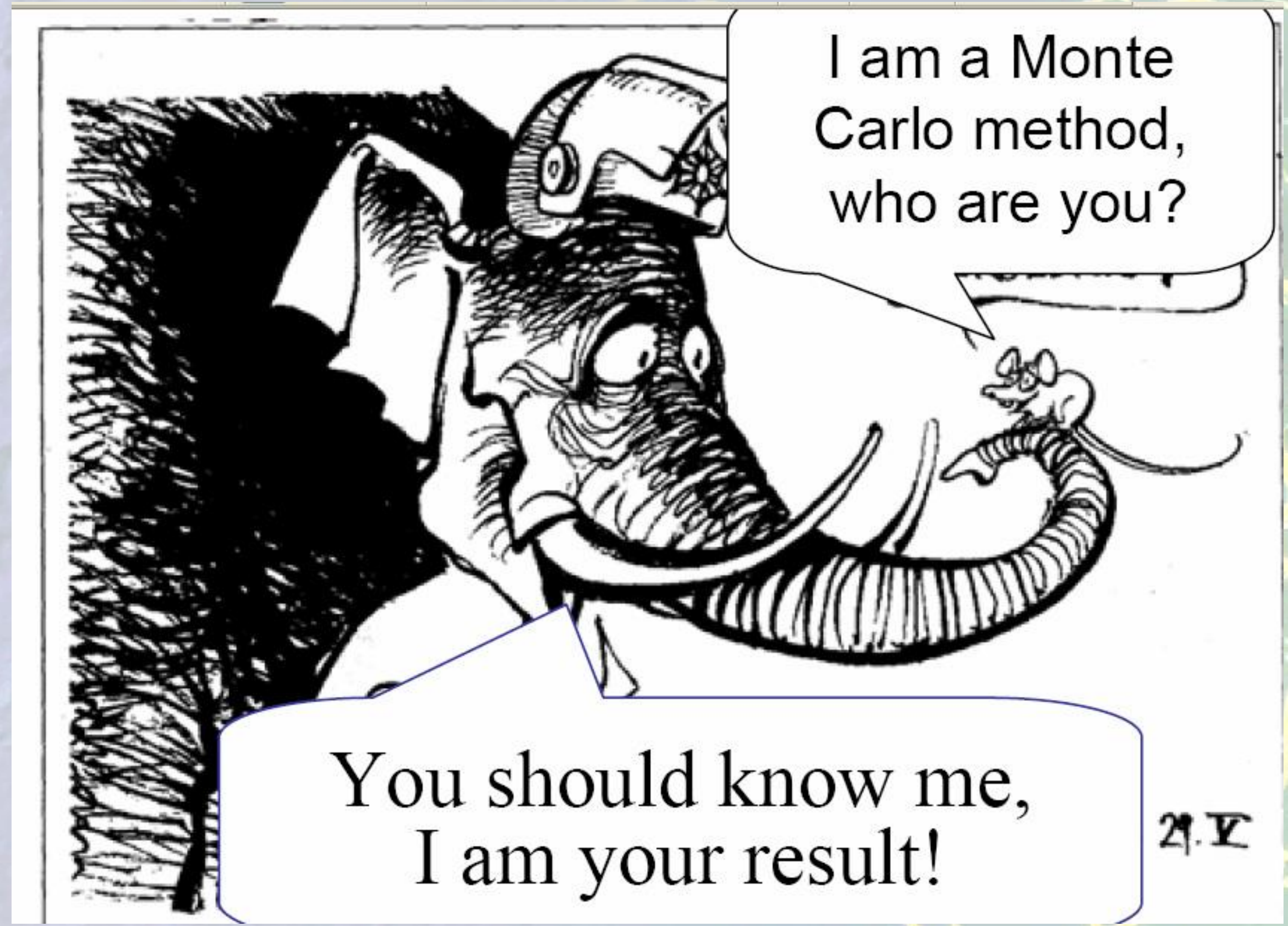
- The various density of the soil at the place of measurement
  - Different physical type of soil horizontally (close to the rivers, tectonically scattered area)
  - Different logs vertically
- Not uniform vertical distribution of the contaminant isotopes (vertical separation by the precipitation or other transport process due to their different chemical behaviour)
- The vertical distribution is not clearly determined or uncertain
- Humidity of the air
  - The Genie2K ISOCS has the option to consider this parameter if it is well known
- Moisture content of the soil
- Precipitation of Rn progenies to the surface by rain (^{212}Pb)

Suggestion for development

- Both the unscattered and scattered gamma photons are detected during the in situ gamma-ray spectrometry
- Most of the HPGe detectors have a factory characterisation which contains the „Peak to Total" calibration. It gives a numerical information regarding the scattering process in the detector.
- From the spectrum and the „Peak to Total" calibration the number of scattered photons on the soil and ambient air can be estimated
- From the in situ gamma-ray spectrum the unscattered photons can be determined easily
- The intrinsic efficiency function of the detector is well known (it must be)

- From these, mentioned above a function should be find to calculate the H*(10)

(My private opinion it is already done for CZT detectors for military purposes.)


I am a Monte Carlo method, who are you?
You should know me, I am your result!

Thank you!

References

ISO 18589-7:2013 Measurement of radioactivity in the environment — Soil —
Part 7: In situ measurement of gamma emitting radionuclide

SPECIFIC ACTIVITY TO H*(10) CONVERSION COEFFICIENTS FOR IN SITU GAMMA SPECTROMETRY
M. Lemercier*, R. Gurriaran, P. Bouisset and X. Cagnat Institut de Radioprotection et de Suˆrete´ Nucle´aire,
Laboratoire de Mesure de la Radioactivite´ de l’Environnement, Baˆt. 501, Bois de Rames, 91400 Orsay, France