L09: In-Situ Contamination & NORMs Measurement

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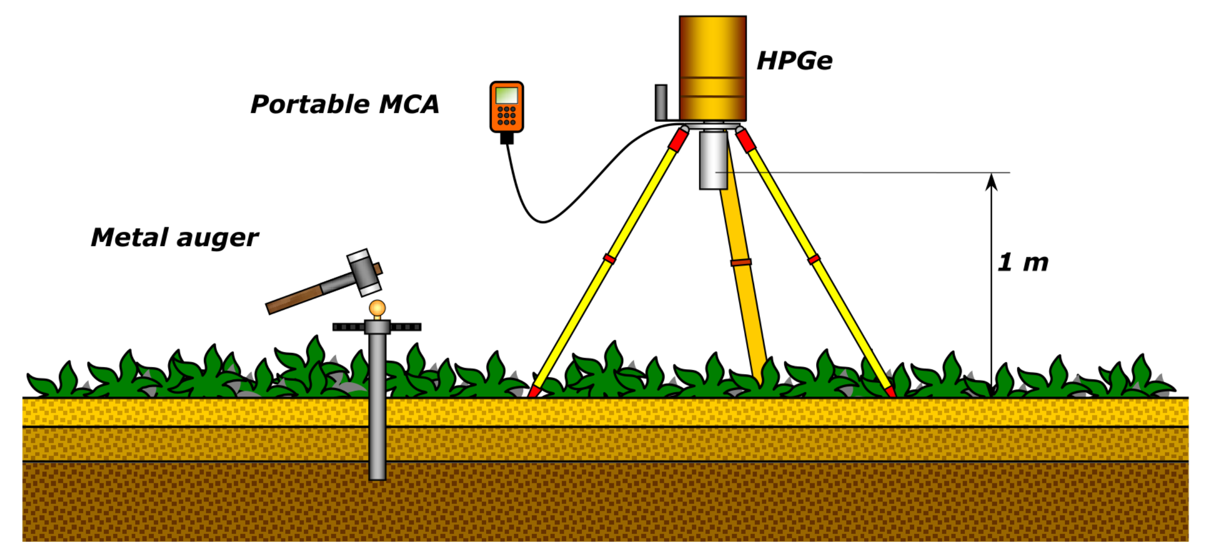
Institue of Nuclear and Physical Engineering

Introduction

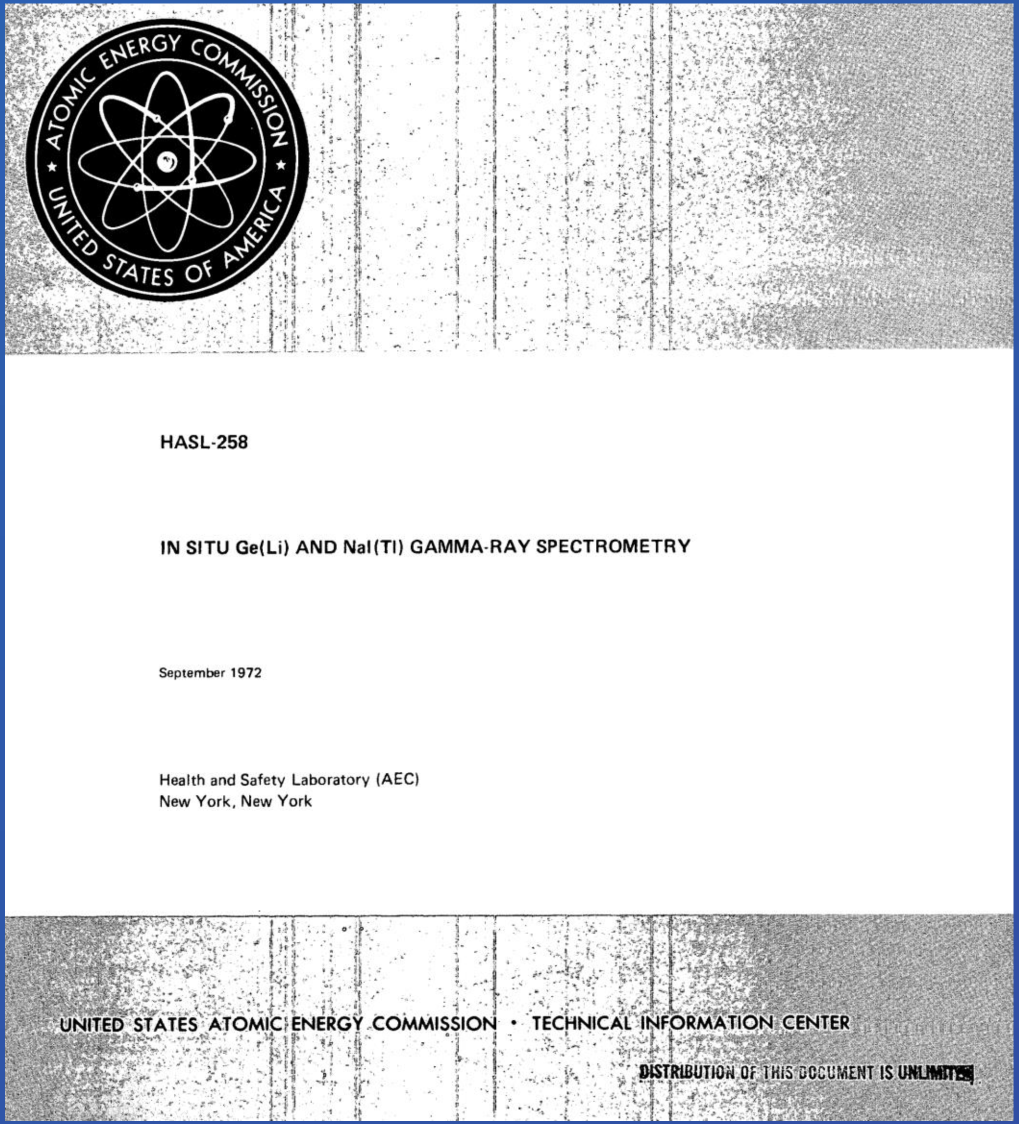
- **Gamma-ray spectrometry measurements performed on site**
  - **In-situ Gamma Spectrometry**
  - Soil Geometry Mesurement
  - Infinite Plane Geometry Mesurement
  - Ground measurement
  - Ground gammaspectrometry
  - Field gammaspectrometry



- **Field of Use**
  - Geology
  - Nuclear energy
  - Radiation protection
  - Radiological mapping

History

- ***1972***
  Beck, H. L., DeCampo, J., and Gogolak, C. In Situ Ge(Li) And Nai(Tl) Gamma-Ray Spectrometry.. United States: N. p., 1972. Web. doi:10.2172/4599415.



HASL-258

IN SITU Ge(Li) AND NaI(Tl) GAMMA-RAY SPECTROMETRY

September 1972

Health and Safety Laboratory (AEC)
New York, New York

UNITED STATES ATOMIC ENERGY COMMISSION • TECHNICAL INFORMATION CENTER

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History

- ***1988***
  Helfer I. K., Miller K. M. Calibration factors for Ge detectors used for field spectrometry. Health Phys. 1988 Jul;55(1):15-29. doi: 10.1097/00004032-198807000-00002. PMID: 3391774.

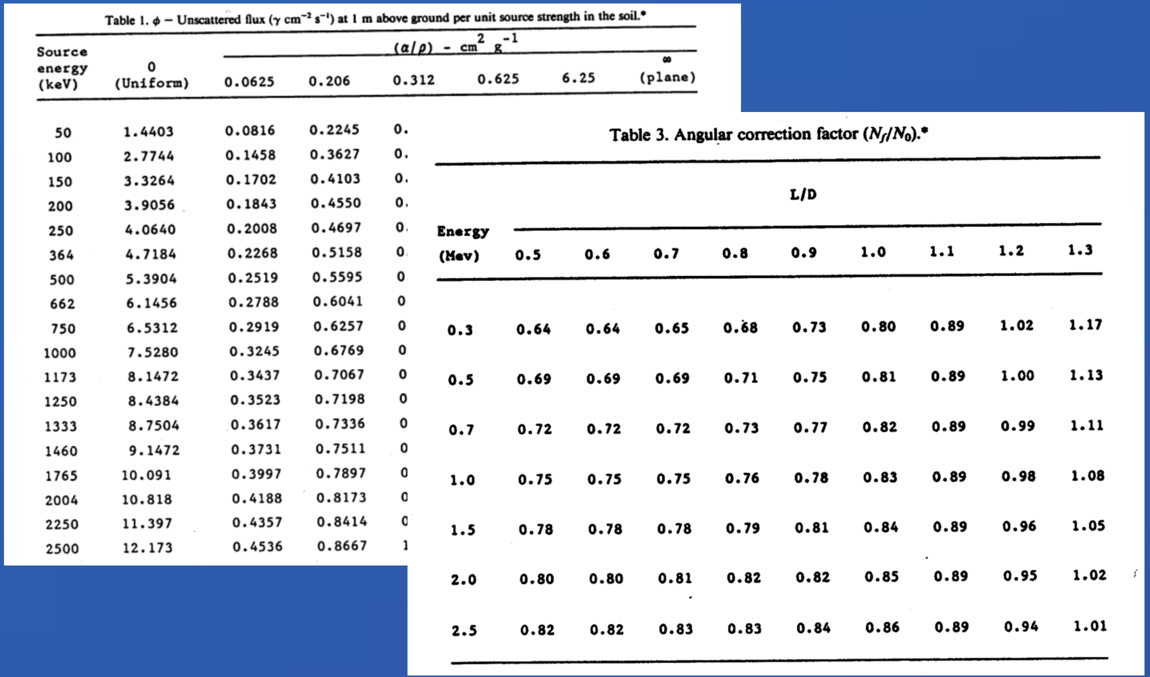
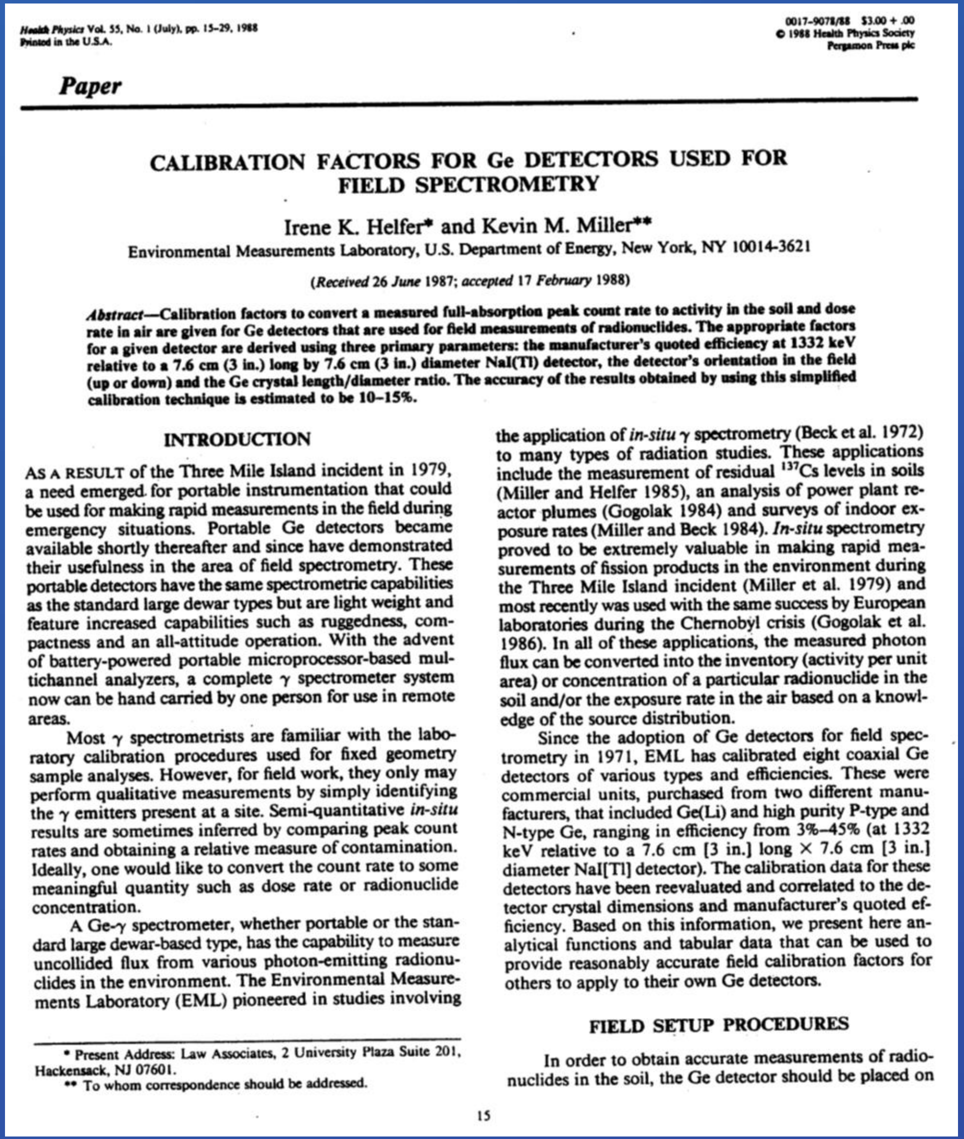


Table 1. ϕ – Unscattered flux (γ cm^{-2} s^{-1}) at 1 m above ground per unit source strength in the soil.*

Source energy (keV)	0 (Uniform)	0.0625	0.206	0.312	0.625	6.25	∞ (plane)
		(α/ρ) - cm^2 g^{-1}					
50	1.4403	0.0816	0.2245	0.			
100	2.7744	0.1458	0.3627	0.			
150	3.3264	0.1702	0.4103	0.			
200	3.9056	0.1843	0.4550	0.			
250	4.0640	0.2008	0.4697	0.			
364	4.7184	0.2268	0.5158	0			
500	5.3904	0.2519	0.5595	0			
662	6.1456	0.2788	0.6041	0			
750	6.5312	0.2919	0.6257	0			
1000	7.5280	0.3245	0.6769	0			
1173	8.1472	0.3437	0.7067	0			
1250	8.4384	0.3523	0.7198	0			
1333	8.7504	0.3617	0.7336	0			
1460	9.1472	0.3731	0.7511	0			
1765	10.091	0.3997	0.7897	0			
2004	10.818	0.4188	0.8173	0			
2250	11.397	0.4357	0.8414	0			
2500	12.173	0.4536	0.8667	1			

Table 3. Angular correction factor (N_f/N_0).*

Energy (Mev)	L/D 0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.3	0.64	0.64	0.65	0.68	0.73	0.80	0.89	1.02	1.17
0.5	0.69	0.69	0.69	0.71	0.75	0.81	0.89	1.00	1.13
0.7	0.72	0.72	0.72	0.73	0.77	0.82	0.89	0.99	1.11
1.0	0.75	0.75	0.75	0.76	0.78	0.83	0.89	0.98	1.08
1.5	0.78	0.78	0.78	0.79	0.81	0.84	0.89	0.96	1.05
2.0	0.80	0.80	0.81	0.82	0.82	0.85	0.89	0.95	1.02
2.5	0.82	0.82	0.83	0.83	0.84	0.86	0.89	0.94	1.01



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Paper

CALIBRATION FACTORS FOR Ge DETECTORS USED FOR FIELD SPECTROMETRY

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Environmental Measurements Laboratory, U.S. Department of Energy, New York, NY 10014-3621

(*Received* 26 *June* 1987; *accepted* 17 *February* 1988)

***Abstract*—Calibration factors to convert a measured full-absorption peak count rate to activity in the soil and dose rate in air are given for Ge detectors that are used for field measurements of radionuclides. The appropriate factors for a given detector are derived using three primary parameters: the manufacturer's quoted efficiency at 1332 keV relative to a 7.6 cm (3 in.) long by 7.6 cm (3 in.) diameter NaI(Tl) detector, the detector's orientation in the field (up or down) and the Ge crystal length/diameter ratio. The accuracy of the results obtained by using this simplified calibration technique is estimated to be 10–15%.**

INTRODUCTION

AS A RESULT of the Three Mile Island incident in 1979, a need emerged for portable instrumentation that could be used for making rapid measurements in the field during emergency situations. Portable Ge detectors became available shortly thereafter and since have demonstrated their usefulness in the area of field spectrometry. These portable detectors have the same spectrometric capabilities as the standard large dewar types but are light weight and feature increased capabilities such as ruggedness, compactness and an all-attitude operation. With the advent of battery-powered portable microprocessor-based multichannel analyzers, a complete γ spectrometer system now can be hand carried by one person for use in remote areas.

Most γ spectrometrists are familiar with the laboratory calibration procedures used for fixed geometry sample analyses. However, for field work, they only may perform qualitative measurements by simply identifying the γ emitters present at a site. Semi-quantitative *in-situ* results are sometimes inferred by comparing peak count rates and obtaining a relative measure of contamination. Ideally, one would like to convert the count rate to some meaningful quantity such as dose rate or radionuclide concentration.

A Ge-γ spectrometer, whether portable or the standard large dewar-based type, has the capability to measure uncollided flux from various photon-emitting radionuclides in the environment. The Environmental Measurements Laboratory (EML) pioneered in studies involving the application of *in-situ* γ spectrometry (Beck et al. 1972) to many types of radiation studies. These applications include the measurement of residual ^{137}Cs levels in soils (Miller and Helfer 1985), an analysis of power plant reactor plumes (Gogolak 1984) and surveys of indoor exposure rates (Miller and Beck 1984). *In-situ* spectrometry proved to be extremely valuable in making rapid measurements of fission products in the environment during the Three Mile Island incident (Miller et al. 1979) and most recently was used with the same success by European laboratories during the Chernobyl crisis (Gogolak et al. 1986). In all of these applications, the measured photon flux can be converted into the inventory (activity per unit area) or concentration of a particular radionuclide in the soil and/or the exposure rate in the air based on a knowledge of the source distribution.

Since the adoption of Ge detectors for field spectrometry in 1971, EML has calibrated eight coaxial Ge detectors of various types and efficiencies. These were commercial units, purchased from two different manufacturers, that included Ge(Li) and high purity P-type and N-type Ge, ranging in efficiency from 3%–45% (at 1332 keV relative to a 7.6 cm [3 in.] long × 7.6 cm [3 in.] diameter NaI[Tl] detector). The calibration data for these detectors have been reevaluated and correlated to the detector crystal dimensions and manufacturer's quoted efficiency. Based on this information, we present here analytical functions and tabular data that can be used to provide reasonably accurate field calibration factors for others to apply to their own Ge detectors.

FIELD SETUP PROCEDURES

In order to obtain accurate measurements of radionuclides in the soil, the Ge detector should be placed on

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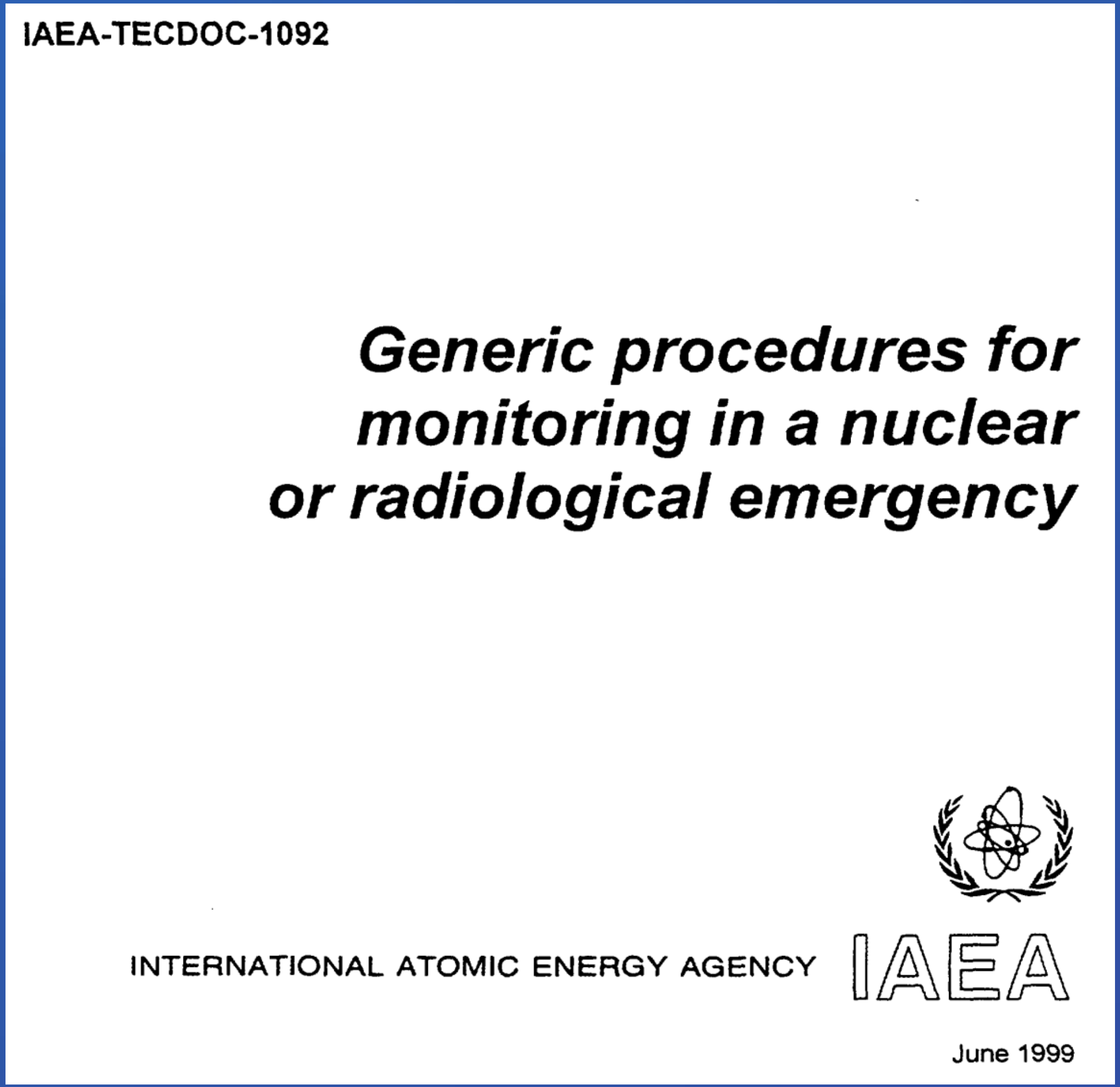
** To whom correspondence should be addressed.

History

- ***1999***
  IAEA-TECDOC-1092
  Generic procedures for monitoring in a nuclear or radiological emergency
  PROCEDURE D.1.a, p 132



IAEA-TECDOC-1092

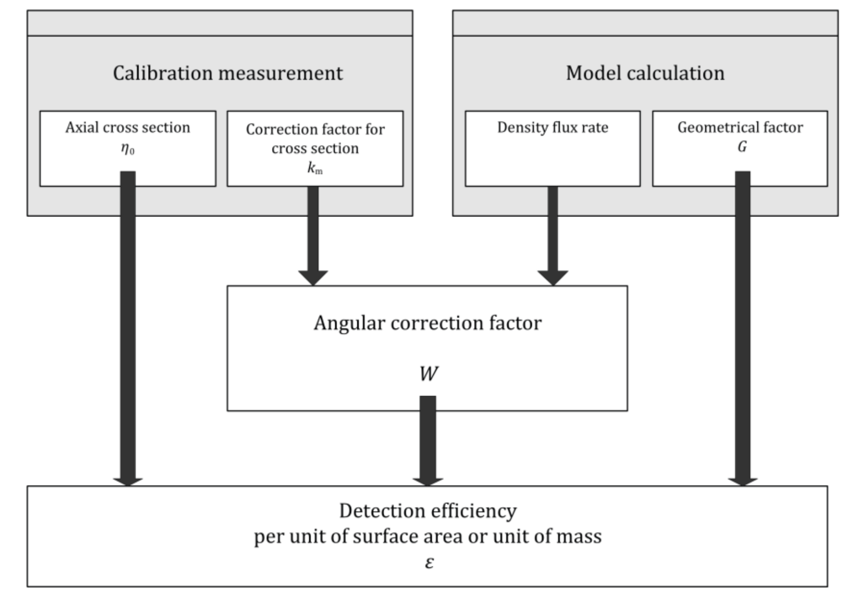
Generic procedures for monitoring in a nuclear or radiological emergency

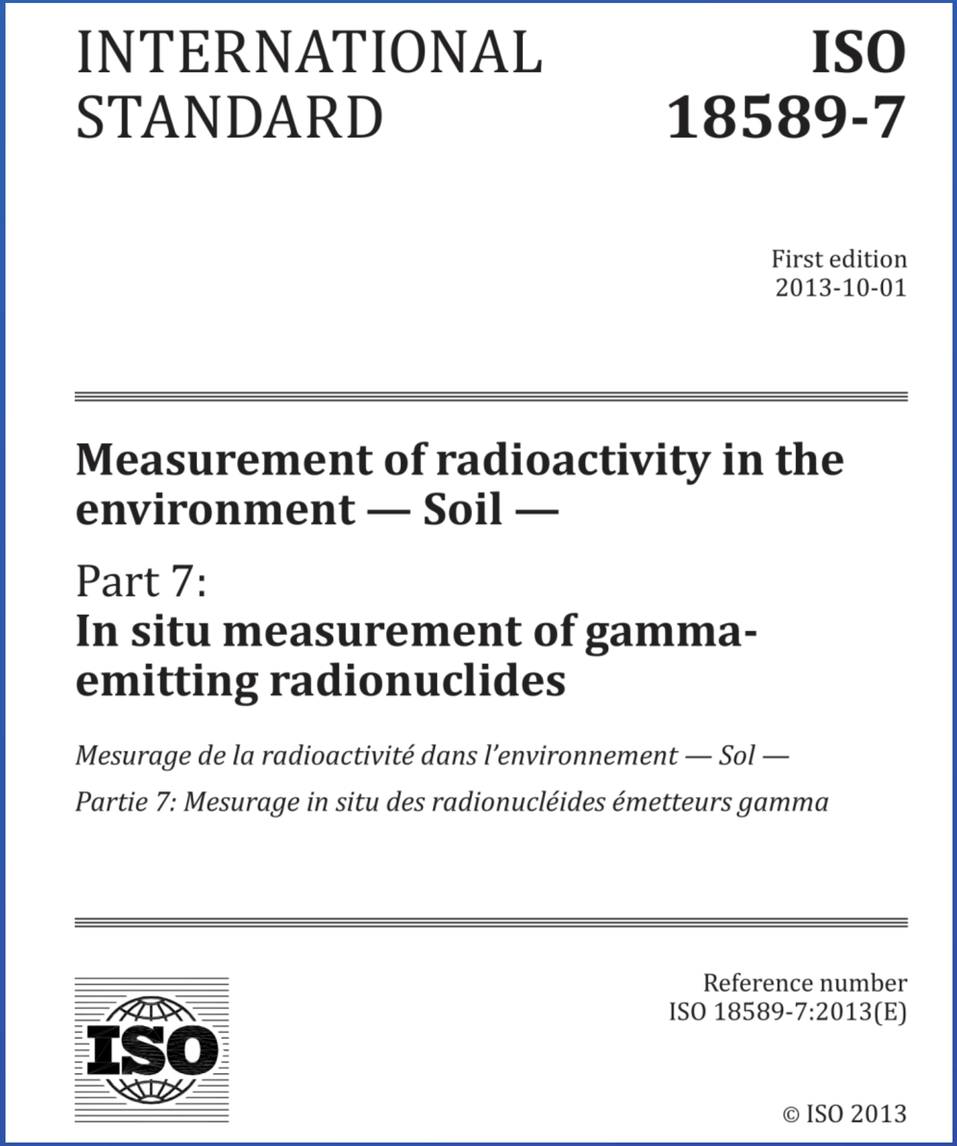
INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

June 1999

History

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





INTERNATIONAL STANDARD

ISO 18589-7

First edition
2013-10-01

Measurement of radioactivity in the environment — Soil —

Part 7:
In situ measurement of gamma-emitting radionuclides

Mesurage de la radioactivité dans l'environnement — Sol —

Partie 7: Mesurage in situ des radionucléides émetteurs gamma

Reference number
ISO 18589-7:2013(E)

Laboratory vs In-Situ Gamma Measurement

	Laboratory measurement	**In-Situ measurement**
Sample information	Well known	Limited and/or estimated
Geometries	Small objects, bottles, beakers, Marinelli beakers	Surfaces, buildings, drums, boxes, large areas
Efficiency Calibration	Etalon available	Etalon not available
Results uncertainties	≈ < 5 %	≈ > 20 %

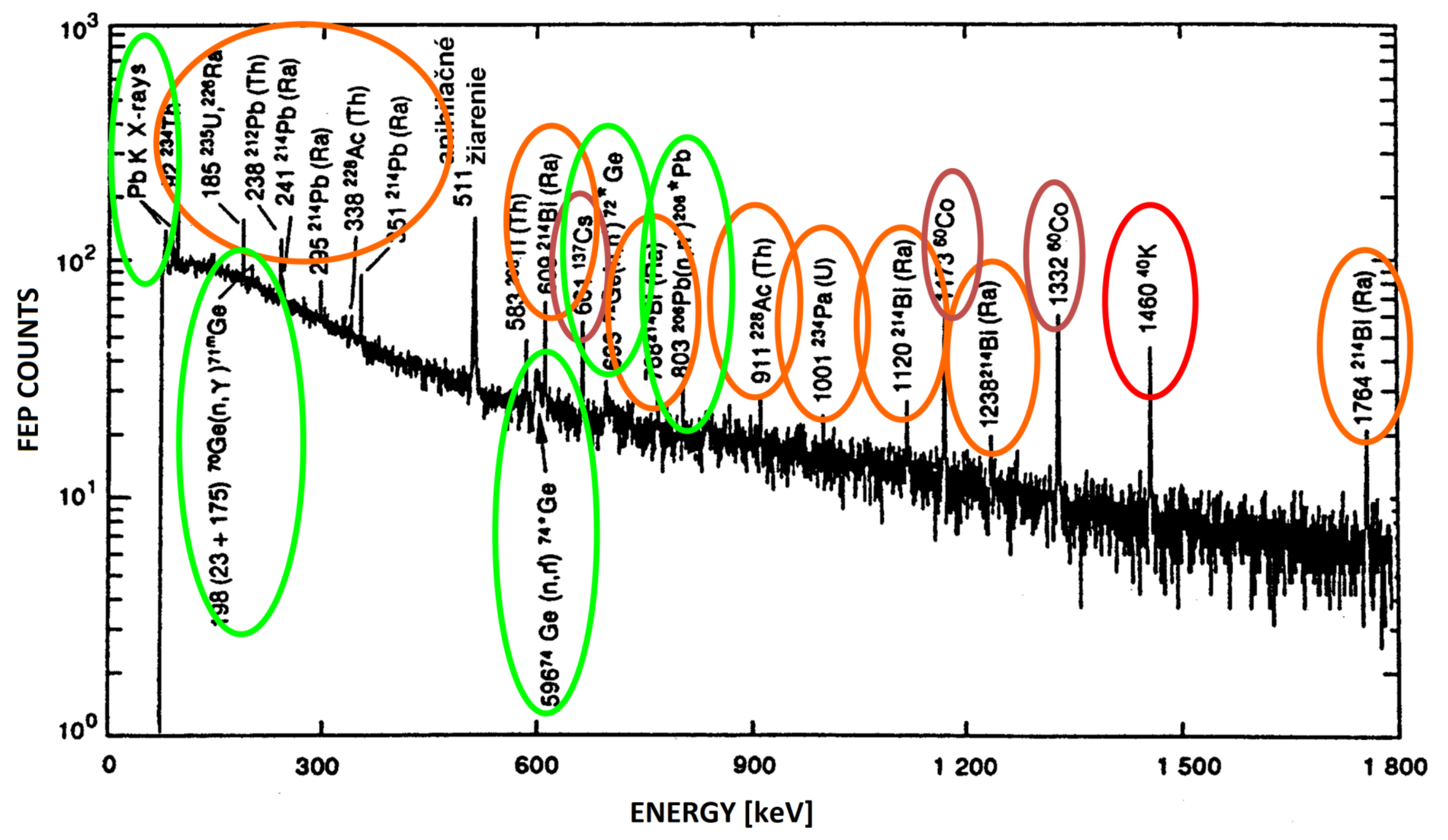
Object vs Ground Measurement

	Object measurement	Ground measurement
Space	Finite	Semi-Infinite
Sample	Container, Box, Package, Spill	Large plane areas
Results	Absolute or mass units Bq, Bq/kg	Surface or mass units Bq/m^2, Bq/kg

Background Radiation

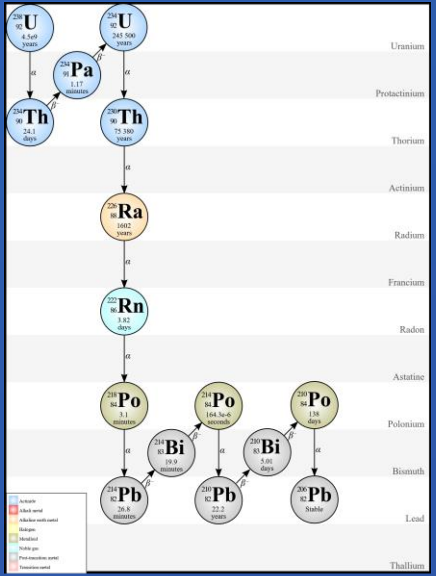
- The nuclides usually measured by gamma spectrometry are the **primordial nuclides**: ^{40}K, ^{235}U, ^{238}U and ^{232}Th.
- A few common reactor **activation and fission products** that are often present in background (^{137}Cs).
- There are, of course, other naturally occurring nuclides, such as ^{14}C, which are produced continuously by nuclear reactions between high-energy particles with oxygen and nitrogen in the earth's atmosphere. Of those, only **^{7}Be** is measurable by gamma spectrometry.
- The major '**fluorescence' X-rays from likely shielding materials** – Pb, Sn, Cd and Cu.

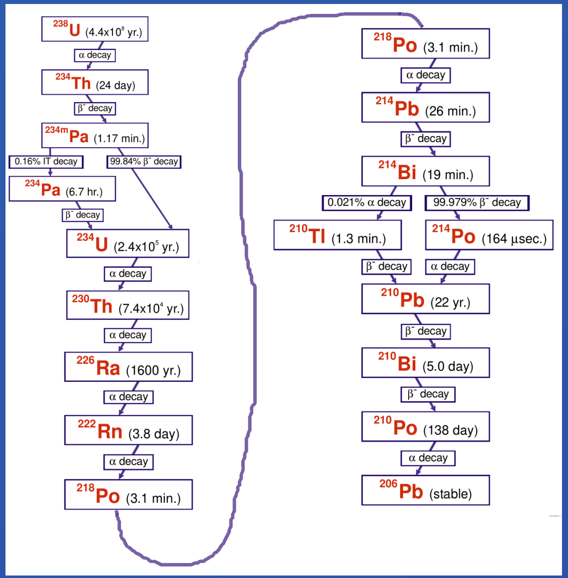
Background Gamma Spectrum

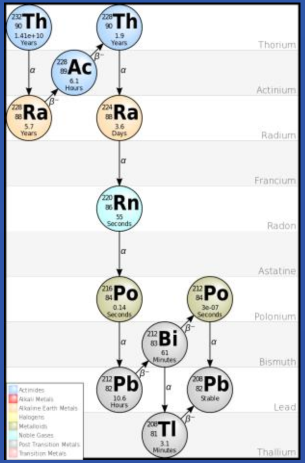


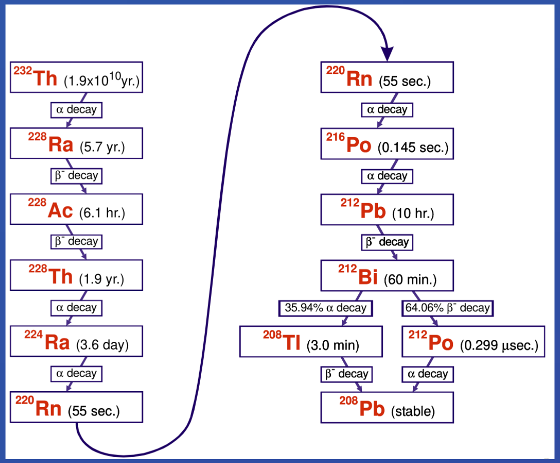
In-Situ Radionuclides

- **Primordial**
  - ^{40}K
  - Decay chains/series
    - Uranium - Radium ^{238}U - ^{214}Pb, ^{214}Bi
    - Thorium ^{232}Th - ^{228}Ac, ^{212}Pb, ^{208}Tl
    - Actinium ^{235}U
- **Artificial – Nuclear weapons and reactors**
  - ^{131}I, ^{134}Cs, ^{137}Cs





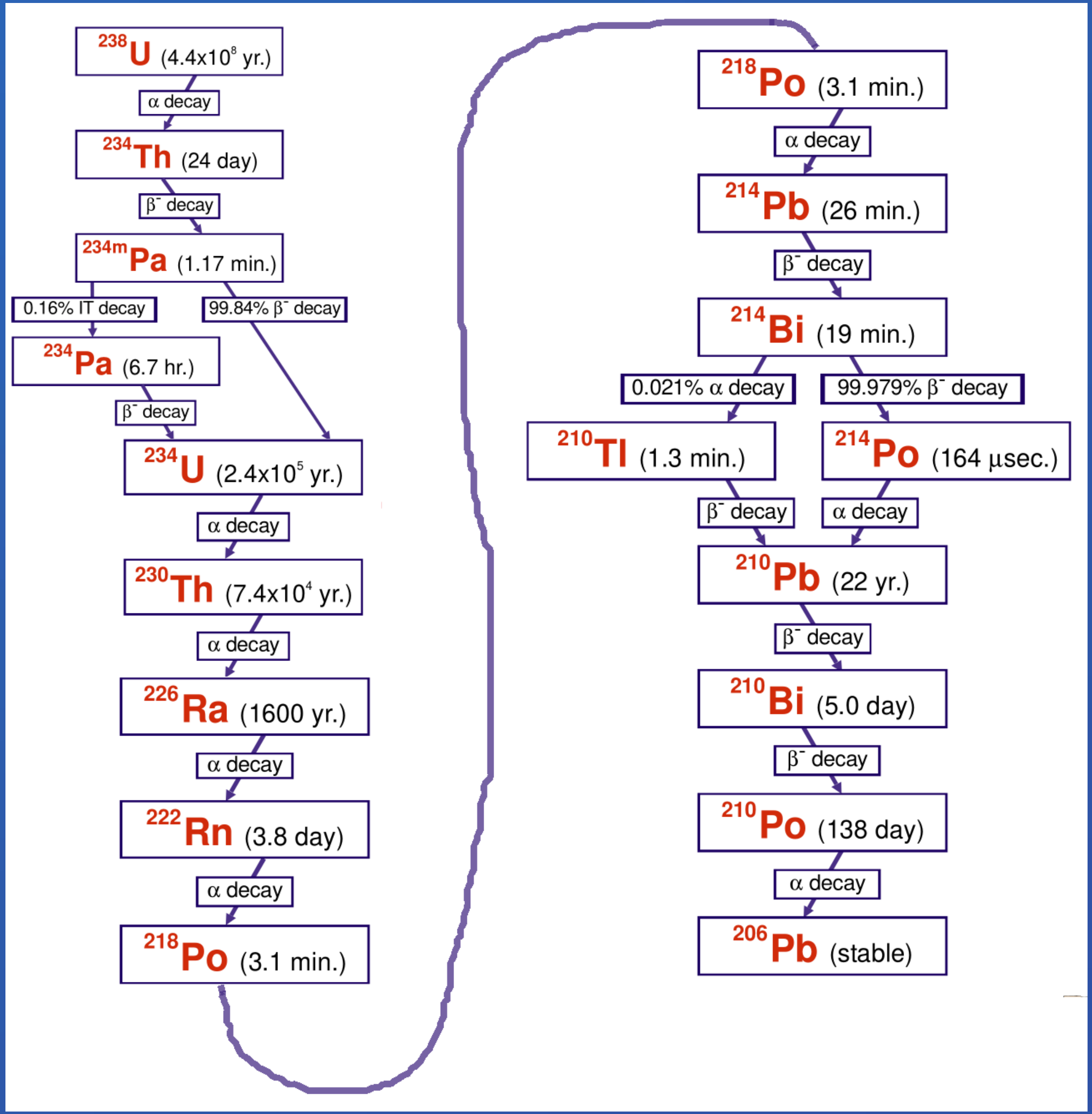




Background Radiation – ^{238}U

- ^{238}U comprises 99.25% of natural uranium. That decays by alpha emission to ^{234}Th which in turn decays to ^{234m}Pa and so on until stable ^{206}Pb is reached.
- If we look at the half-lives of the various nuclides, they are all much less than the half-life of ^{238}U. This means that, in a natural, undisturbed source of uranium, every daughter nuclide will be in secular equilibrium with the ^{238}U. The activity of each daughter nuclide will be equal to the ^{238}U activity.
- **There are 14 radionuclides in the chain and so the total activity of such a source will be 14 times that of the parent, or of any individual nuclide.**

Background Radiation – ^{238}U



^{238}U (4.4x10^{8} yr.)

α decay

^{234}Th (24 day)

β^{-} decay

^{234m}Pa (1.17 min.)

0.16% IT decay

99.84% β^{-} decay

^{234}Pa (6.7 hr.)

β^{-} decay

^{234}U (2.4x10^{5} yr.)

α decay

^{230}Th (7.4x10^{4} yr.)

α decay

^{226}Ra (1600 yr.)

α decay

^{222}Rn (3.8 day)

α decay

^{218}Po (3.1 min.)

^{218}Po (3.1 min.)

α decay

^{214}Pb (26 min.)

β^{-} decay

^{214}Bi (19 min.)

0.021% α decay

99.979% β^{-} decay

^{210}Tl (1.3 min.)

^{214}Po (164 μsec.)

β^{-} decay

α decay

^{210}Pb (22 yr.)

β^{-} decay

^{210}Bi (5.0 day)

β^{-} decay

^{210}Po (138 day)

α decay

^{206}Pb (stable)

Background Radiation – ^{235}U

- ^{235}U comprises 0.72 % of natural uranium.
- The decay series involves 12 nuclides in 11 decay stages and the emission of 7 alpha particles
- Within this series, only ^{235}U itself can readily be measured.
- **In the gamma spectra of NORM is the mutual interference between ^{235}U (185.72 keV) and ^{226}Ra (186.21 keV).**
- Assume that the entire 186 keV peak is due to ^{226}Ra and correct the result.

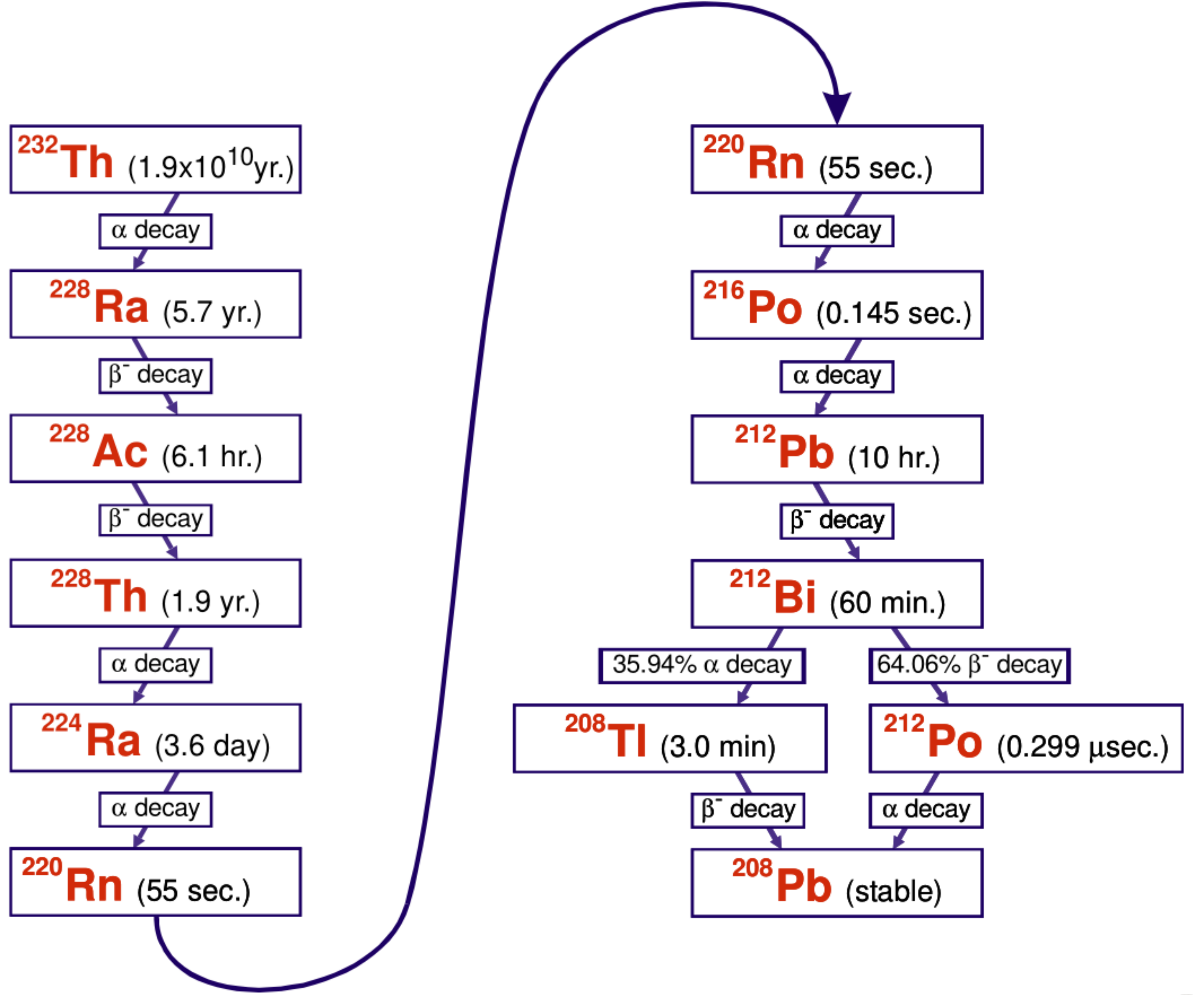
Corrected ^{226}Ra = 0,5709×Apparent ^{226}Ra

Estimated ^{235}U = 0,02662×Apparent ^{226}Ra

Background Radiation – ^{232}Th

- Natural thorium is 100 % ^{232}Th. Six alpha particles are emitted during ten decay stages. Four nuclides can be measured easily by gamma spectrometry: ^{228}Ac, ^{212}Pb, ^{212}Bi and ^{208}Tl.
- The decay of ^{212}Bi is branched – only 35.94 % of decays produce ^{208}Tl by alpha decay.
- If a ^{208}Tl measurement is to be used to estimate the thorium activity, it must be divided by 0.3594 to correct for the branching.

Background Radiation – ^{232}Th



^{232}Th (1.9x10^{10}yr.)

α decay

^{228}Ra (5.7 yr.)

β$^-$ decay

^{228}Ac (6.1 hr.)

β$^-$ decay

^{228}Th (1.9 yr.)

α decay

^{224}Ra (3.6 day)

α decay

^{220}Rn (55 sec.)

^{220}Rn (55 sec.)

α decay

^{216}Po (0.145 sec.)

α decay

^{212}Pb (10 hr.)

β$^-$ decay

^{212}Bi (60 min.)

35.94% α decay

64.06% β$^-$ decay

^{208}Tl (3.0 min)

^{212}Po (0.299 μsec.)

β$^-$ decay

α decay

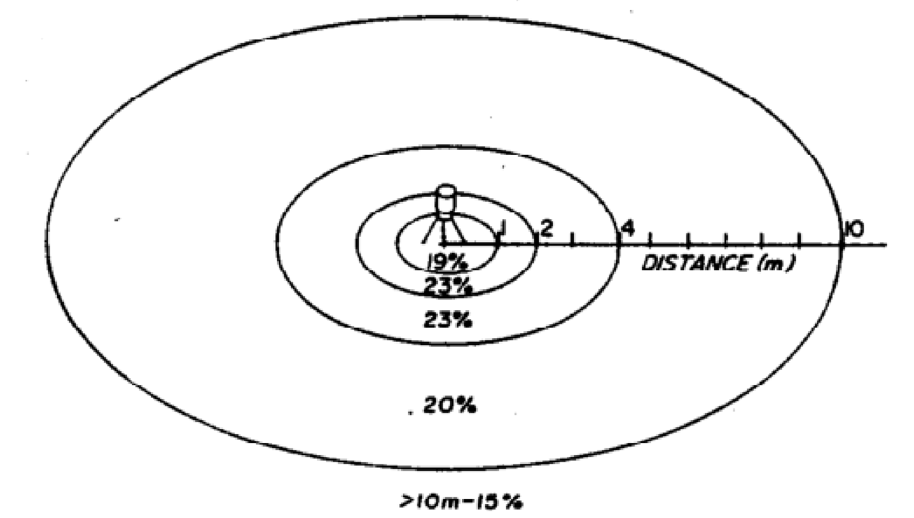
^{208}Pb (stable)

Background Radiation – ^{40}k

- ^{40}K is very evident in background spectra. It is present as **0.17% of natural potassium** and is present in wood and building materials and even in the bodies of the gamma spectrometrists.
- The substantial presence of ^{40}K in the detector background and in many samples, with its long Compton continuum, severely restricts the limit of detection of the many nuclides emitting gamma rays at lower energies
- 1460.83 keV

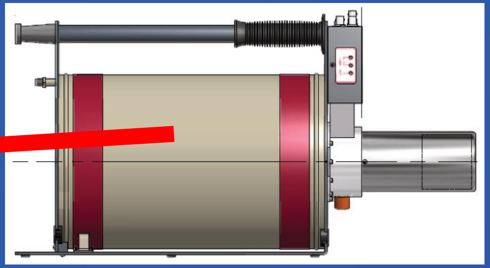
Measurement Conditions

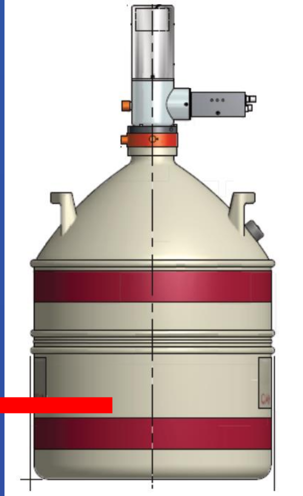
- No buildings, forest, objects (at least 20 m - 30 m radius.
- No people (at least 5 metres)
- Vertical position of detector (down)
- 1 m detector/surface distance
- Energy > 60 – 100 keV



Detectors

- **HPGe**
  - LN_2 detector + analyser + computer
  - Portable electrically cooled
- **Scintillation NaI:Tl or $LaBr_3$:Ce**
  - Limited resolution
- **Orientation of the detector**
  - Down (preferable)
  - Up (laboratory configuration with Dewar)





Efficiency Calibration - 3 approaches

- Empirical approach – based on the calibration standard measurements
  - Calibration based on using calibration standards (phantoms)

- Numerical approach (modelling)– based on the numerical calculations
  - Possible to calculate any shape
  - Mathematical simulations (MCNP, Geant4, ISOCS SW)

- Combination of modelling and empirical approach
  - For example, ISOTOPIC SW (Pont source, DOE-EML % method)

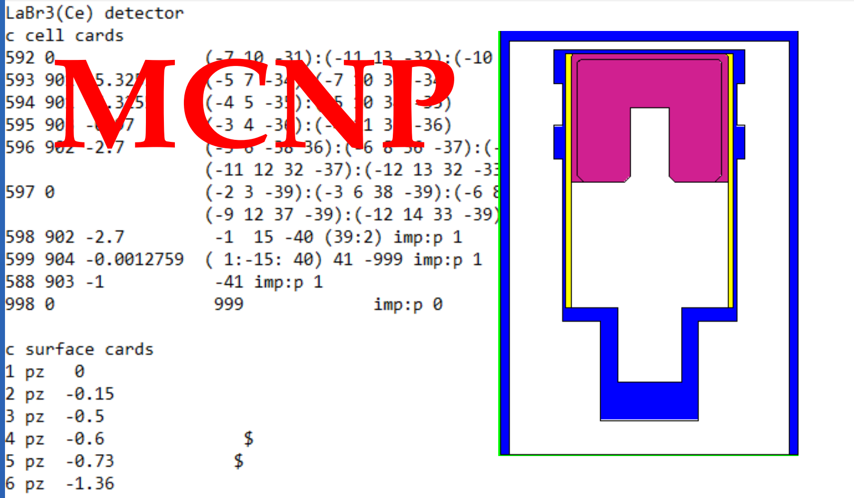
Empirical Approach

- Spectra evaluation based on the **Peak Net Area** counts
- Calibration standard geometry = Sample geometry

$$\boxed{\varepsilon(E) = \frac{N}{S \times t \times \gamma}} \qquad A = \frac{N}{\varepsilon \times t \times \gamma}$$

$\varepsilon(\mathrm{E})$	**is efficiency,**
N	net counts in full-energy peak area,
S	activity of certified calibration source
γ	emission probability of the gamma-ray with energy E
t	time of measurement
A	activity of sample

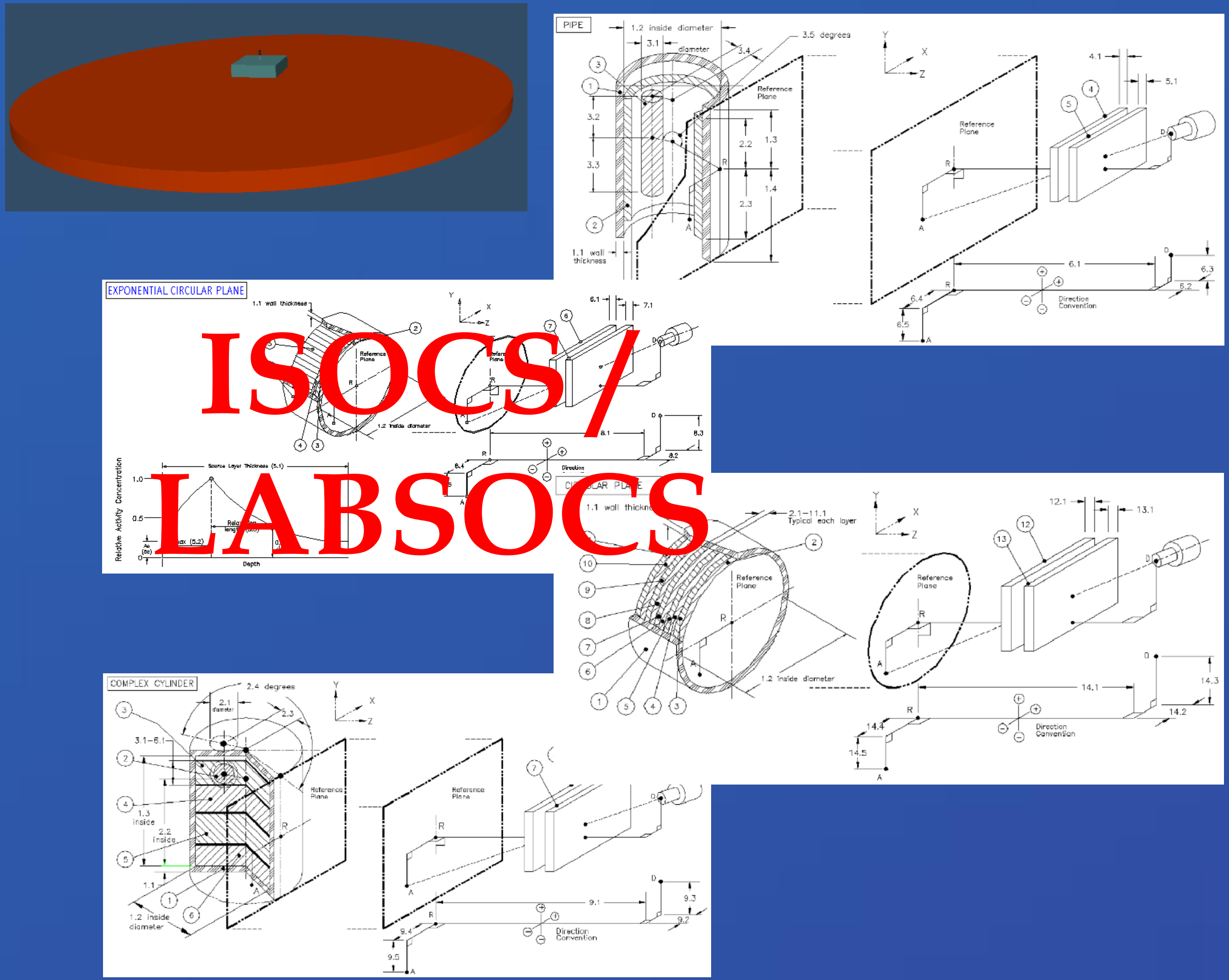
Modelling Approach



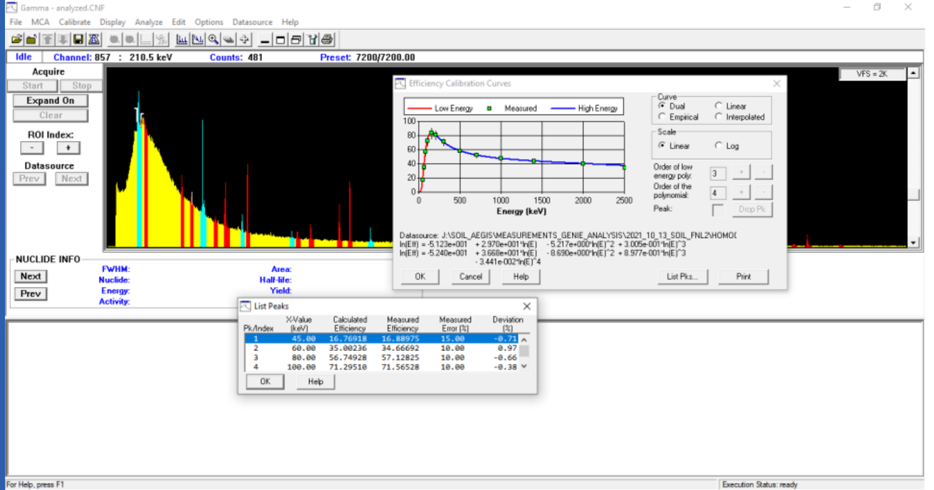
MCNP

```
LaBr3(Ce) detector
c cell cards
592 0                  (-7 10 -31):(-11 13 -32):(-10
593 90[illegible]5.32[illegible]       (-5 7 -34):(-7 10 3[illegible] -34
594 90[illegible].325[illegible]       (-4 5 -35):([illegible]5 10 3[illegible]35)
595 90[illegible] -[illegible]7       (-3 4 -36):(-[illegible]1 3[illegible] -36)
596 902 -2.7           ([illegible] 6 -38 36):(-6 8 36 -37):(-
                       (-11 12 32 -37):(-12 13 32 -33
597 0                  (-2 3 -39):(-3 6 38 -39):(-6 8
                       (-9 12 37 -39):(-12 14 33 -39)
598 902 -2.7            -1  15 -40 (39:2) imp:p 1
599 904 -0.0012759  ( 1:-15: 40) 41 -999 imp:p 1
588 903 -1              -41 imp:p 1
998 0                   999           imp:p 0

c surface cards
1 pz    0
2 pz   -0.15
3 pz   -0.5
4 pz   -0.6             $
5 pz   -0.73           $
6 pz   -1.36
```



ISOCS / LABSOCS



Gamma - analyzed.CNF

Idle Channel: 857 : 210.5 keV Counts: 481 Preset: 7200/7200.00

FWHM: Nuclide: Energy: Activity: Area: Half-life: Yield:

Curve: ● Dual ○ Linear ○ Empirical ○ Interpolated

Scale: ● Linear ○ Log

Order of low energy poly: 3

Order of the polynomial: 4

Peak: ☐

Datasource: J:\SOIL_AEGIS\MEASUREMENTS_GENIE_ANALYSIS\2021_10_13_SOIL_FNL2\HOMO(

ln(Eff) = -5.123e+001 + 2.970e+001*ln(E) - 5.217e+000*ln(E)^2 + 3.005e-001*ln(E)^3

ln(Eff) = -5.240e+001 + 3.668e+001*ln(E) - 8.690e+000*ln(E)^2 + 8.977e-001*ln(E)^3 - 3.441e-002*ln(E)^4

Pk/Index	X-Value (keV)	Calculated Efficiency	Measured Efficiency	Measured Error (%)	Deviation (%)
1	45.00	16.76918	16.88975	15.00	-0.71
2	60.00	35.00236	34.66692	10.00	0.97
3	80.00	56.74928	57.12825	10.00	-0.66
4	100.00	71.29510	71.56528	10.00	-0.38

For Help, press F1

Execution Status: ready

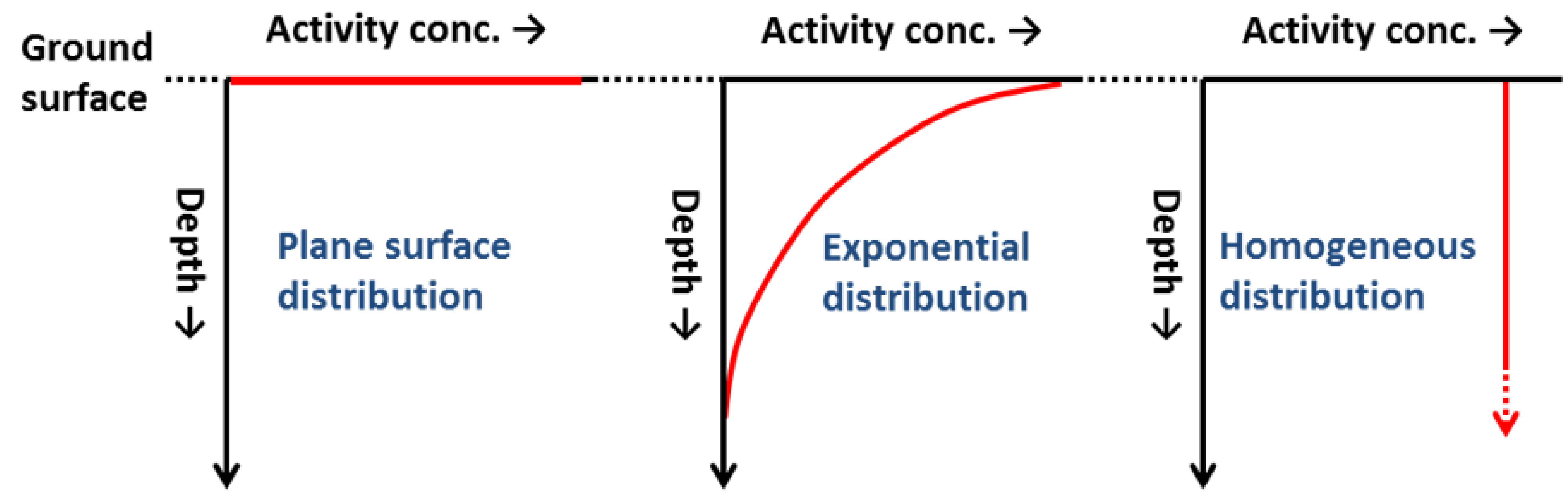
Efficiency Calibration - Problems

- Calibration standard - unavailable
- Distribution of radionuclides in the soil – assumed and/or unavailable

?

Activity depth distribution

- **3 cases, differ in depth distribution**
  - Fresh Fallout
  - Aged Fallout
  - Homogeneous distribution



Activity depth distribution

- The depth source distribution in the soil can be described by so-called $\boldsymbol{\alpha/\rho}$ parameter or ***ß*** parameter

L [cm]	relaxation length (length, where concentration decreases e-times)
α [cm^{-1}]	1 / relaxation length
ρ [$\mathrm{g\ cm}^{-3}$]	density
α/ρ [$\mathrm{cm}^{2}\ \mathrm{g}^{-1}$]	α/ρ parameter
ß [$\mathrm{g\ cm}^{-2}$]	relaxation mass per unit area, α/ρ =1/ ß

Uniform source distribution (NORM)

$$\boldsymbol{\alpha/\rho = 0} \quad \textbf{\textit{or}} \quad \text{ß} = \infty$$

Surface source distribution in the soil (fresh fallout)

$$\boldsymbol{\alpha/\rho = \infty} \quad \textbf{\textit{or}} \quad \text{ß} = \mathbf{0}$$

Exponential source distribution in the soil (aged fallout)

$$\mathbf{0} < \boldsymbol{\frac{\alpha}{\rho}} < \infty \quad \textbf{\textit{or}} \quad \mathbf{0} < \text{ß} < \infty$$

Activity depth distribution

Distribution	Uniform	Surface	Exponential
Result unit	Bq kg^{-1}	Bq m^{-2}	Bq m^{-2}
α/ρ	0	∞	$0 < \alpha/\rho < \infty$
ß	∞	0	0 < ß < ∞
Nuclides	NORM K-40 and decay chains	Fresh fallout Fission products	Aged fallout

$\alpha/\rho = 0.206$ [$cm^2 \cdot g^{-1}$] ≈≈ relaxation length of 3 cm, soil density 1,65 gcc - very frequently used value for aged fallout

Activity distribution estimation

- **Sampling – depth profile**
- **Multiple line – line to line method**

Calibration Approach

BASED ON THE POINT SOURCES MEASUREMENTS AND MATHEMATICAL MODEL OF THE SAMPLE.

- Beck, H. L., DeCampo, J., and Gogolak, C. In Situ Ge(Li) And Nai(Tl) Gamma-Ray Spectrometry.. United States: N. p., **1972**. Web. doi:10.2172/4599415.
- Helfer I. K., Miller K. M. Calibration factors for Ge detectors used for field spectrometry. Health Phys. **1988** Jul;55(1):15-29. doi: 10.1097/00004032-198807000-00002. PMID: 3391774.
- IAEA-TECDOC-1092
  Generic procedures for monitoring in a nuclear or radiological emergency
- ISO 18589-7 Measurement of radioactivity in the environment — Soil — Part 7: In situ measurement of gamma-emitting radionuclides

Efficiency Calibration Approach

- **Beck, Helfer, Miller**
  ...and older publications.

$$\varepsilon(E) = \frac{N_f}{A} = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

- $\frac{N_0}{\Phi}$ response factor (intrinsic efficiency of the detector)
- $\frac{N_f}{N_0}$ angular correction factor
- $\frac{\Phi}{A}$ geometrical factor (incident flux arriving to the detector per unit inventory of the radionuclide in the soil)

Efficiency Calibration Approach

- **ISO 18589-7**

$$\varepsilon(E) = \frac{N_f}{A} = n_0 \times \mathbf{W} \times \mathbf{G}$$

- n_0 response factor (intrinsic efficiency of the detector)
- W angular correction factor
- G geometrical factor (incident flux arriving to the detector per unit inventory of the radionuclide in the soil)

Nomenclature Comparison

Older literature $\varepsilon(E) = \dfrac{N_f}{A} = n_0 \times W \times G$

ISO $\varepsilon(E) = \dfrac{N_f}{A} = \dfrac{N_0}{\Phi} \times \dfrac{N_f}{N_0} \times \dfrac{\Phi}{A}$

RESPONSE FACTOR

ANGULAR CORRECTION FACTOR

GEOMETRICAL FACTOR

Response factor $\frac{N_0}{\Phi}$

Peak count rate due to a unit primary photon flux density of Energy E incident on the detector along the detector axis (normal to the detector face)

Based on the PS measurement

$$\frac{N_0}{\Phi} = \frac{\frac{P_i}{T}}{\frac{Y \times A}{4\pi r^2}} = \frac{4\pi r^2 \times P_i}{Y \times A \times T}$$

$r\ [cm]$	is the source to detector distance
$P_i\ [-]$	is net count in the full energy peak for energy E
$Y\ [-]$	is gamma yield per decay for photons of energy E
$A\ [Bq]$	is activity of point source
$T\ [s]$	is the measuring time

Based on Helfer & Miller relationships

$$\ln\left(\frac{N_0}{\Phi}\right) = a' + b' \ln(E)$$

$\varepsilon_{rel}\ [\%]$ is relative efficiency of the detector

$$a' = 2.689 + 0.4996 \times ln(\varepsilon_{rel}) + 0.0969 \times ln^2(\varepsilon_{rel})$$

$$b' = -1.315 + 0.02044 \times \varepsilon_{rel} - 0.00012 \times \varepsilon_{rel}^2$$

Response factor $\frac{N_0}{\Phi}$

Correct formula

$$\Phi = \frac{Y \times A}{4\pi r^2} \boxed{e^{-\mu_a x} e^{-\mu_h h}}$$

Negligible

$$e^{-\mu_a x} e^{-\mu_h h} \approx 1$$

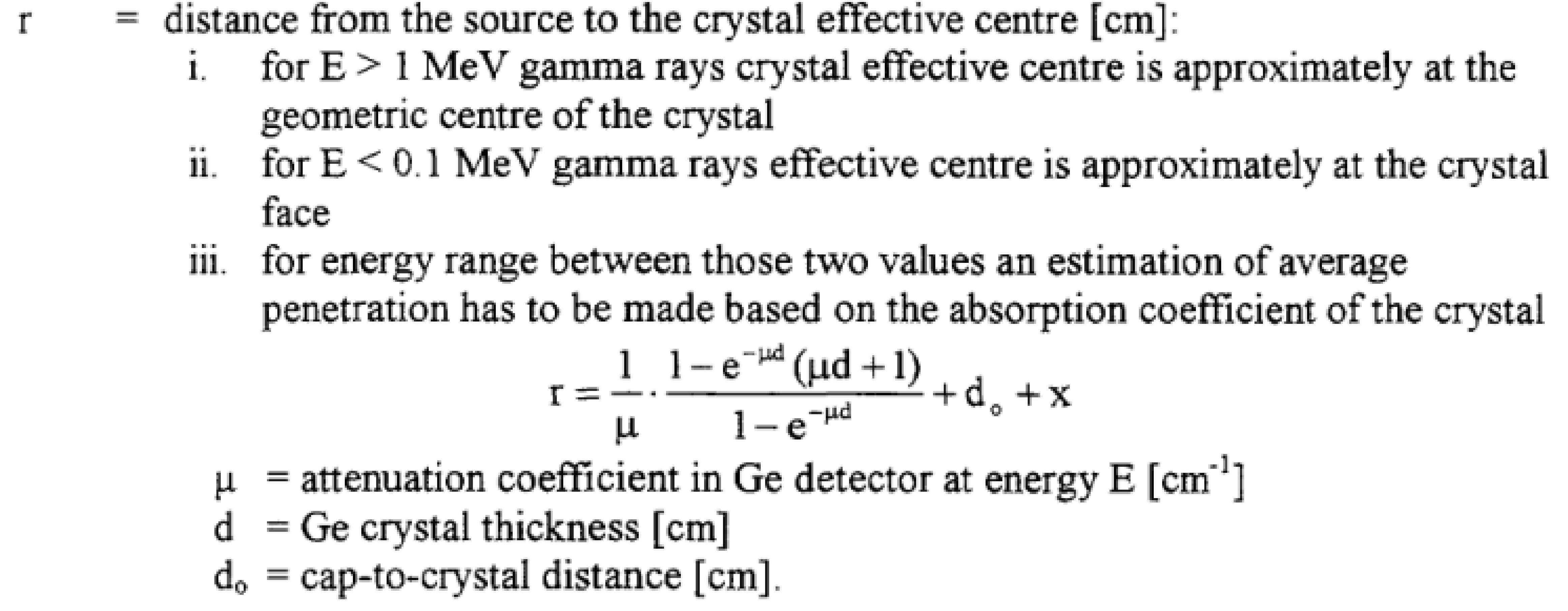
$\mu_a\ [cm^{-1}]$	is linear attenuation coefficient for gammas in air
$x\ \ [cm]$	is detector endcap to source crystal holder
$\mu_h\ [cm^{-1}]$	is linear attenuation coefficient for gam. in source holder
$h\ \ [cm]$	is source holder thickness

Linear attenuation coefficient in air, r = 100 cm, air density 0.00129 gcc

E = 100 keV	μ_a = 2.03 E-2 cm^{-1}	$e^{-\mu_a x}$ = 0.980*
E = 500 keV	μ_a = 1.12 E-2 cm^{-1}	$e^{-\mu_a x}$ = 0.989*
E = 1 MeV	μ_a = 8.15 E-3 cm^{-1}	$e^{-\mu_a x}$ = 0.992*
E = 5 MeV	μ_a = 3.55 E-3 cm^{-1}	$e^{-\mu_a x}$ = 0.996*
E = 10 MeV	μ_a = 2.67 E-3 cm^{-1}	$e^{-\mu_a x}$ = 0.997*

*Ref.: https://physics.nist.gov/cgi-bin/Xcom/xcom2

Response factor $\frac{N_0}{\Phi}$



r = distance from the source to the crystal effective centre [cm]:

- i. for E > 1 MeV gamma rays crystal effective centre is approximately at the geometric centre of the crystal
- ii. for E < 0.1 MeV gamma rays effective centre is approximately at the crystal face
- iii. for energy range between those two values an estimation of average penetration has to be made based on the absorption coefficient of the crystal

$$r = \frac{1}{\mu} \cdot \frac{1 - e^{-\mu d}(\mu d + 1)}{1 - e^{-\mu d}} + d_o + x$$

μ = attenuation coefficient in Ge detector at energy E [cm^{-1}]

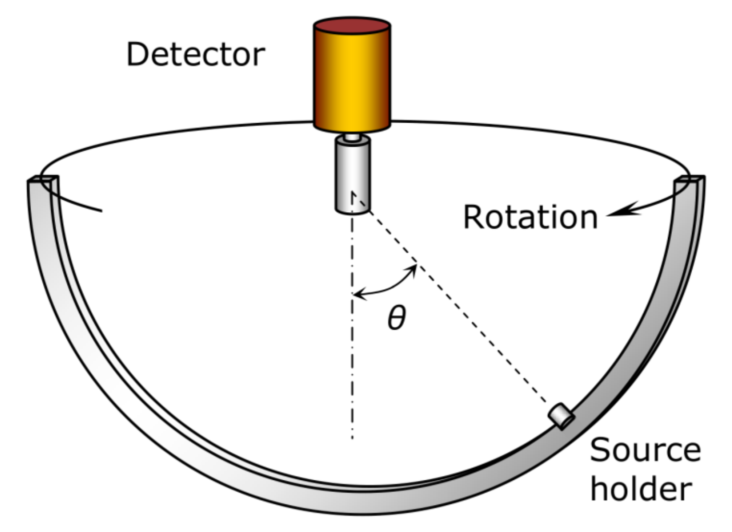
d = Ge crystal thickness [cm]

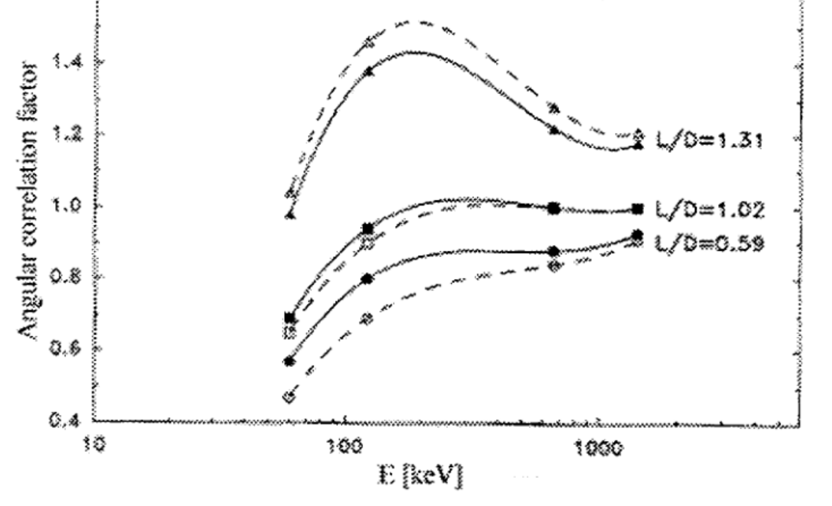
d_o = cap-to-crystal distance [cm].

Angular correction factor $\frac{N_f}{N_0}$

$$\frac{N_f}{N_0} = \frac{\int R(\theta)\Phi(\theta)d\theta}{\int \Phi(\theta)d\theta}$$

- It depends on the detector and source distribution in the soil
- Angular correction factor can be calculated from the measurement according to the equation
- ISO 18589-7: Ba-133 + Eu-152 or mixed gamma point sources





Angular correction factor $\frac{N_f}{N_0}$

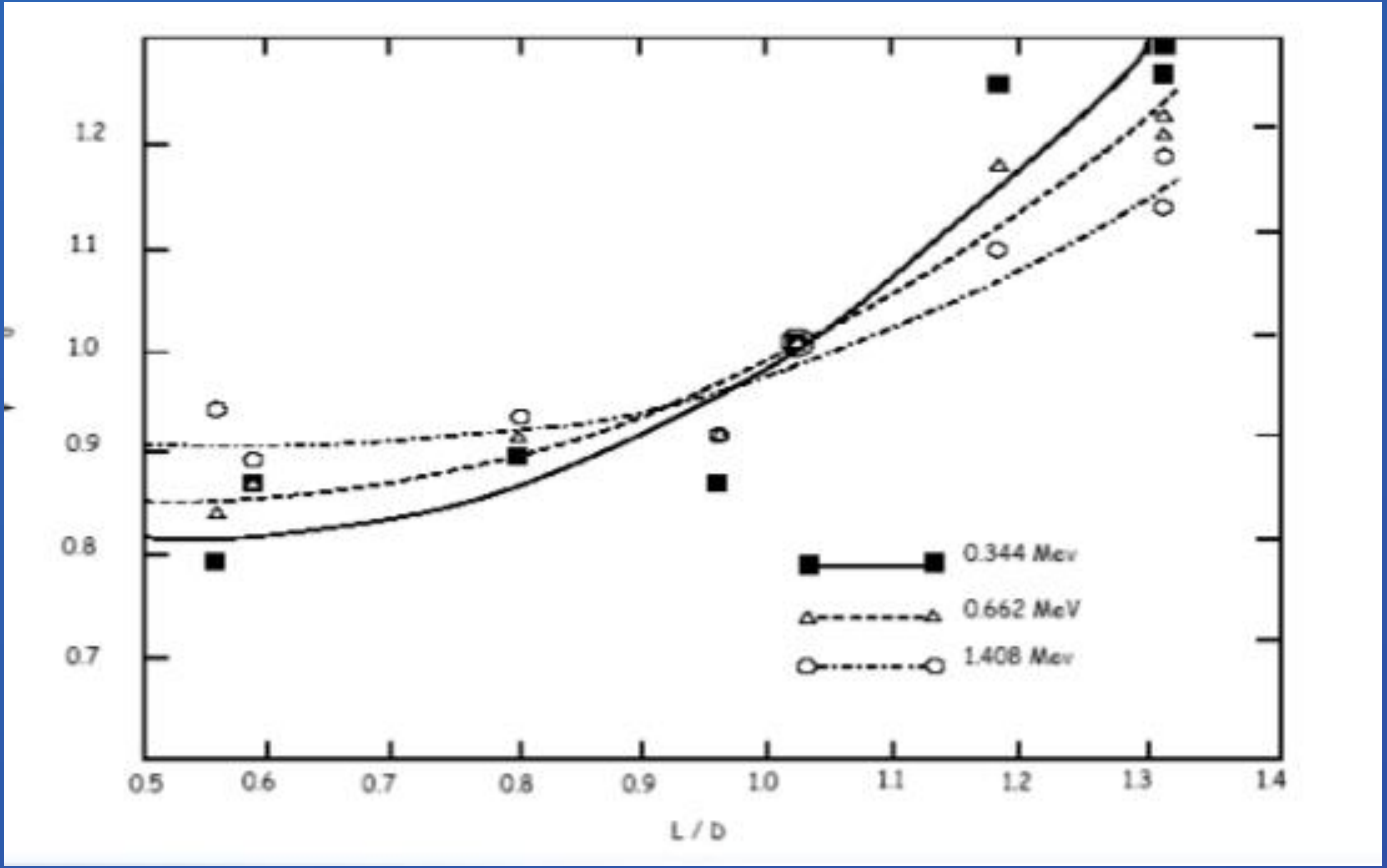
$$\frac{N_f}{N_0} = \frac{\int R(\theta)\Phi(\theta)d\theta}{\int \Phi(\theta)d\theta}$$

$$R(\theta) = \frac{\frac{P_\theta}{t_\theta}}{\frac{P_0}{t_0}}$$

$R(\theta)$	peak count rate for gamma rays of energy E at angle θ relative to count rate at angle $\theta = 0$
$\Phi(\theta)$	gamma ray flux at energy E at angle θ
$\frac{P_\theta}{t_\theta}$	peak count rate for gamma rays of energy E at angle θ
$\frac{P_0}{t_0}$	peak count rate for gamma rays of energy E at angle $\theta = 0$

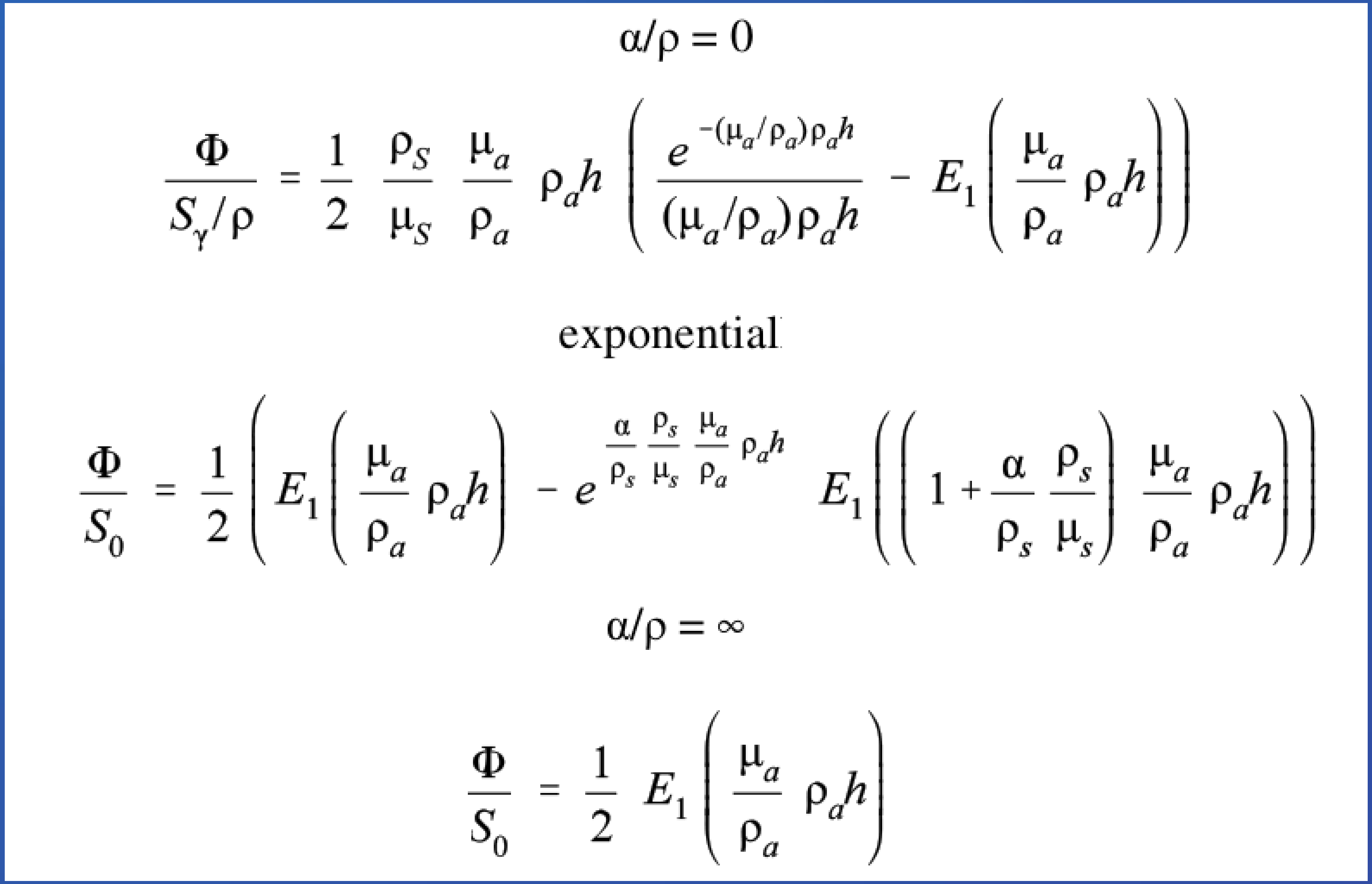
Angular correction factor $\frac{N_f}{N_0}$

Dependent on crystal length/diameter ratio



Geometrical factor $\frac{\Phi}{A}$

- parameter Φ/A is incident flux arriving at the detector per unit activity of the source
- not dependent on detector, but it is function of soil density, soil composition, air attenuation and the source distribution in the soil.



$\alpha/\rho = 0$

$$\frac{\Phi}{S_\gamma/\rho} = \frac{1}{2}\,\frac{\rho_S}{\mu_S}\,\frac{\mu_a}{\rho_a}\,\rho_a h\left(\frac{e^{-(\mu_a/\rho_a)\rho_a h}}{(\mu_a/\rho_a)\rho_a h} - E_1\left(\frac{\mu_a}{\rho_a}\,\rho_a h\right)\right)$$

exponential

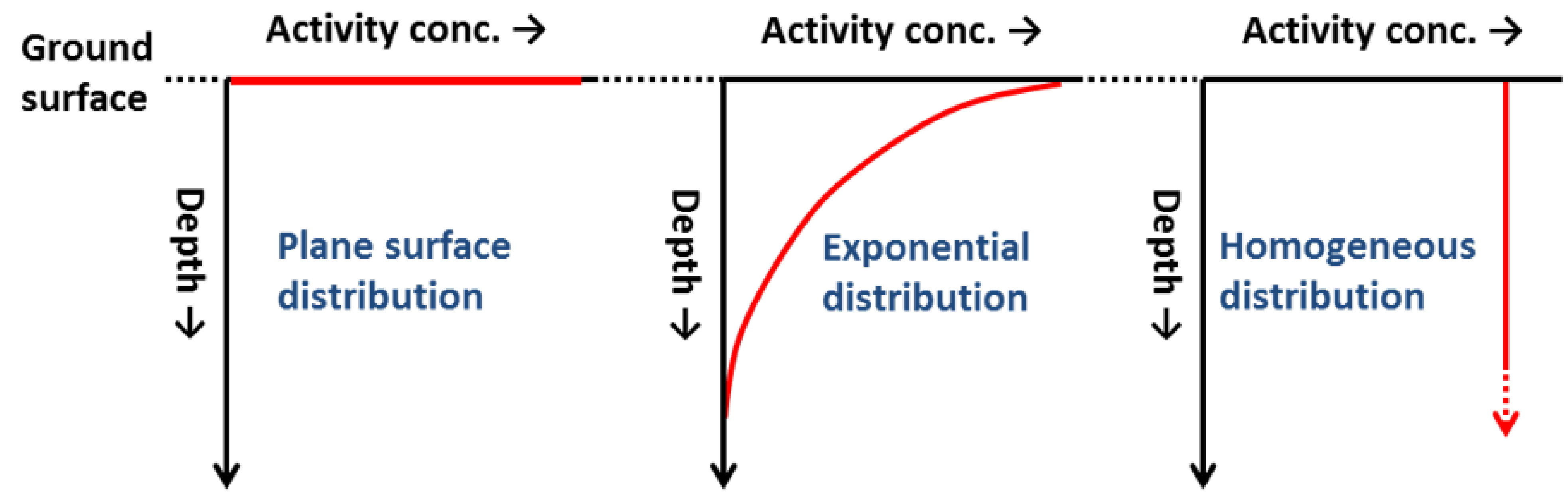
$$\frac{\Phi}{S_0} = \frac{1}{2}\left(E_1\left(\frac{\mu_a}{\rho_a}\,\rho_a h\right) - e^{\frac{\alpha}{\rho_s}\frac{\rho_s}{\mu_s}\frac{\mu_a}{\rho_a}\rho_a h}\,E_1\left(\left(1+\frac{\alpha}{\rho_s}\,\frac{\rho_s}{\mu_s}\right)\frac{\mu_a}{\rho_a}\,\rho_a h\right)\right)$$

$\alpha/\rho = \infty$

$$\frac{\Phi}{S_0} = \frac{1}{2}\,E_1\left(\frac{\mu_a}{\rho_a}\,\rho_a h\right)$$

Activity depth distribution

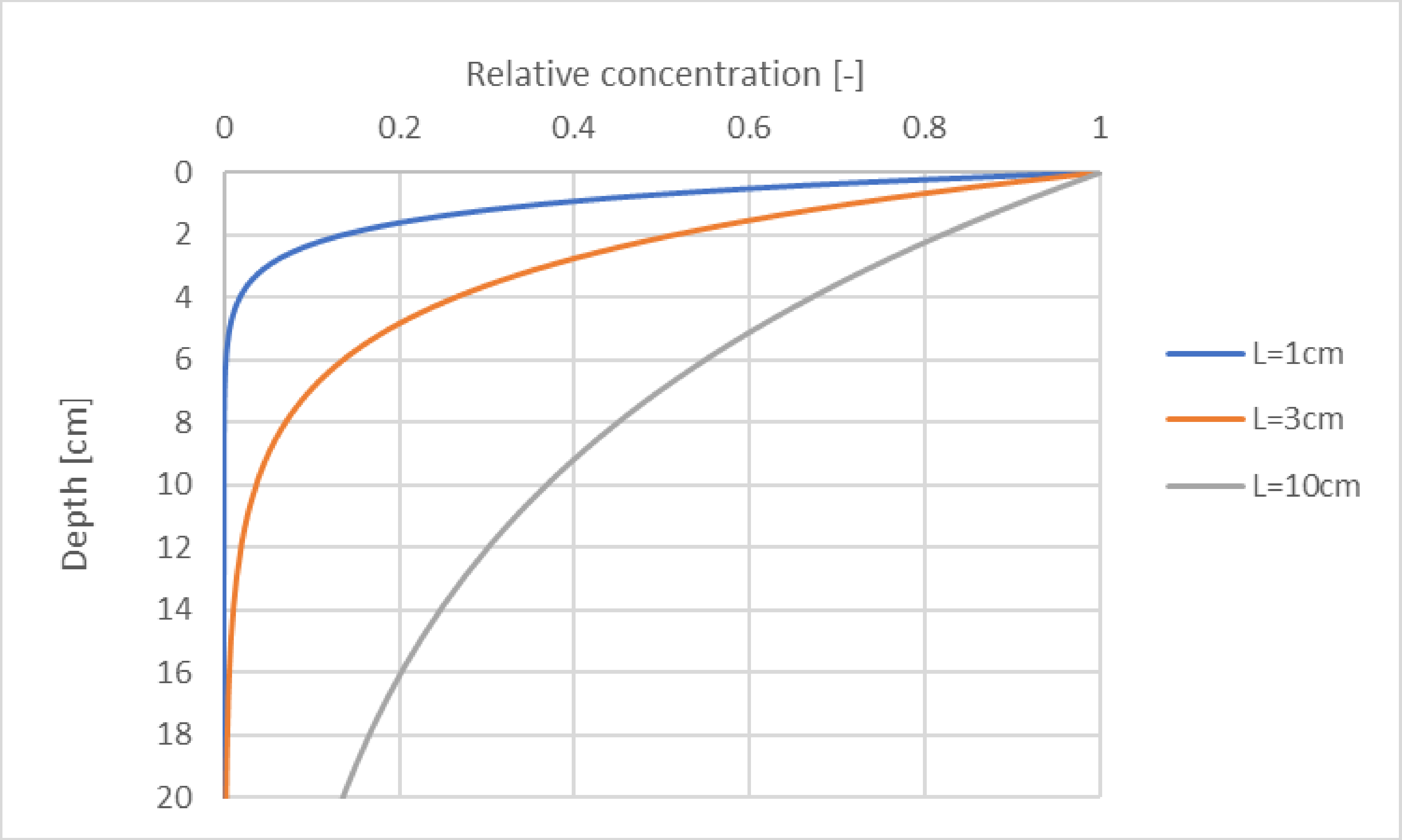
- **3 cases, differ in depth distribution**
  - Fresh Fallout
  - Aged Fallout
  - Homogeneous distribution



Activity depth distribution

Vertical distribution		L cm			
		1 cm	2 cm	3 cm	5 cm
Depth	1 cm	0.632	0.393	0.283	0.181
	2 cm	0.233	0.239	0.204	0.149
	3 cm	0.085	0.145	0.145	0.121
	4 cm	0.032	0.088	0.104	0.100
	5 cm	0.011	0.053	0.075	0.081
	10 cm	0.007	0.082	0.153	0.233
	15 cm	x	x	0.036	0.085
	20 cm	x	x	x	0.032
	25 cm	x	x	x	0.011

Activity depth distribution



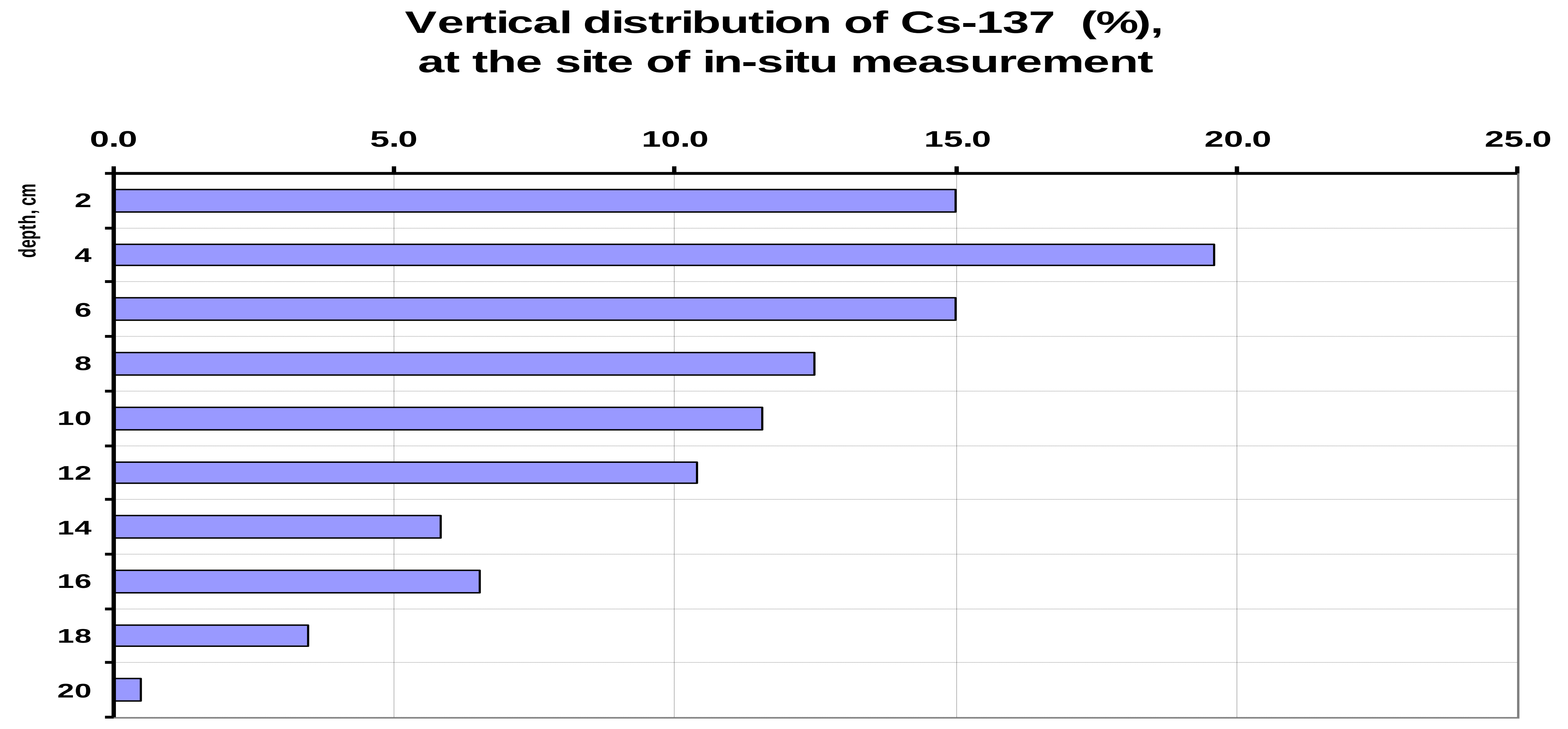
The effect of the detector position and soil density ^{137}Cs, L=3cm

Soil density: 1.05 gcc			
	95 cm	100 cm	105 cm
Efficiency	1.34E-04	1.33E-04	1.32E-04
a, Bq/m^2	1771	1777	1786
Soil density: 1.6 gcc			
a, Bq/m^2		2317	

The effect of the soil density and relaxation length for ^{137}Cs, L=3cm

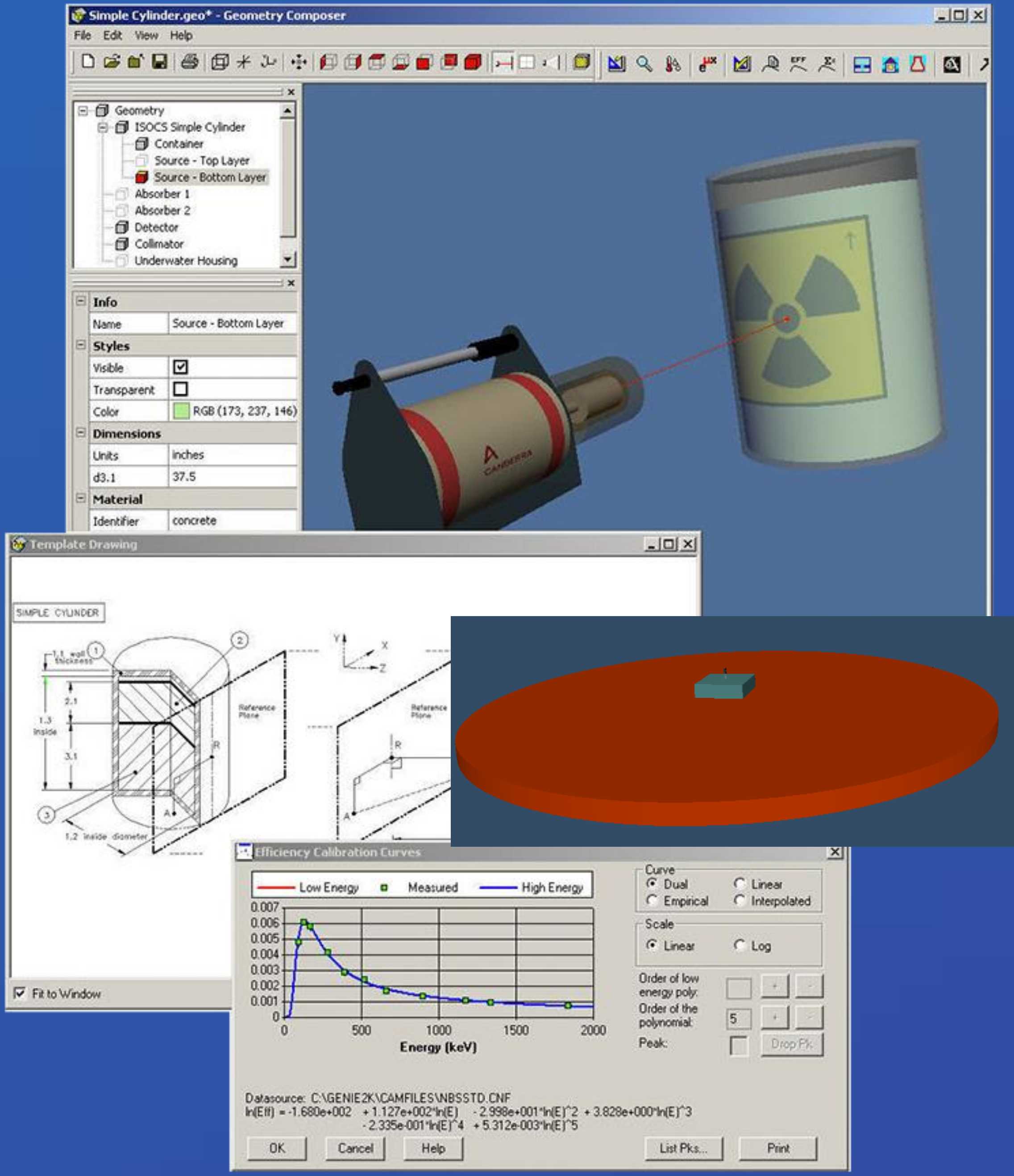
L, cm	1,05 kg/dm^3	1,6 kg/dm^3
1	1005	552
2	1276	1571
3	1777	2317
5	2302	3128

Real Depth Distribution



ISOCS

- Efficiency calibration SW for In Situ Object Counting System
- **Detector is already characterized by 5 step process**
  - Traceable validation sources
  - Characterization measurements
  - MCNP Modelling
  - Detector characterization grid generation
  - Verification of characterization



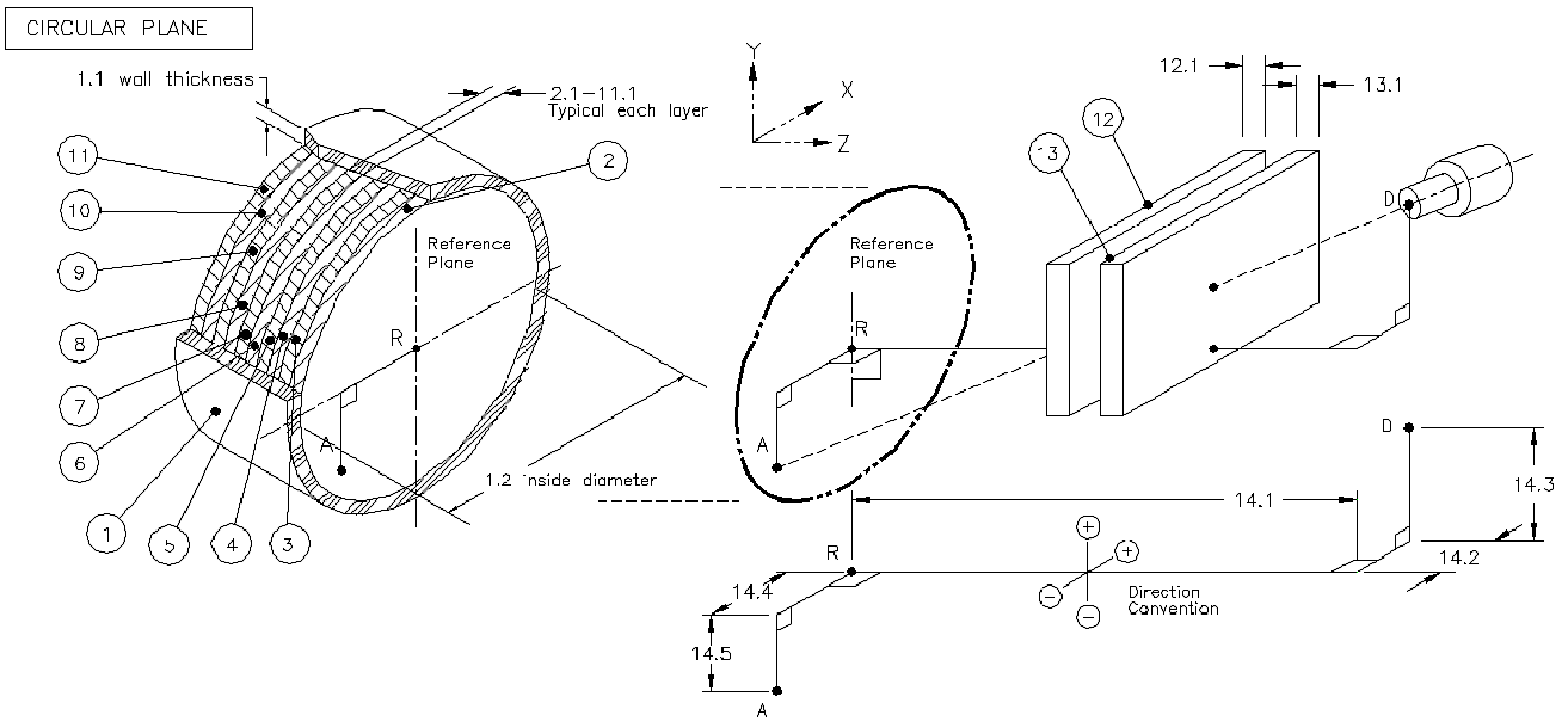
Name: Source - Bottom Layer
Visible: ☑
Transparent: ☐
Color: RGB (173, 237, 146)
Units: inches
d3.1: 37.5
Identifier: concrete

☑ Fit to Window

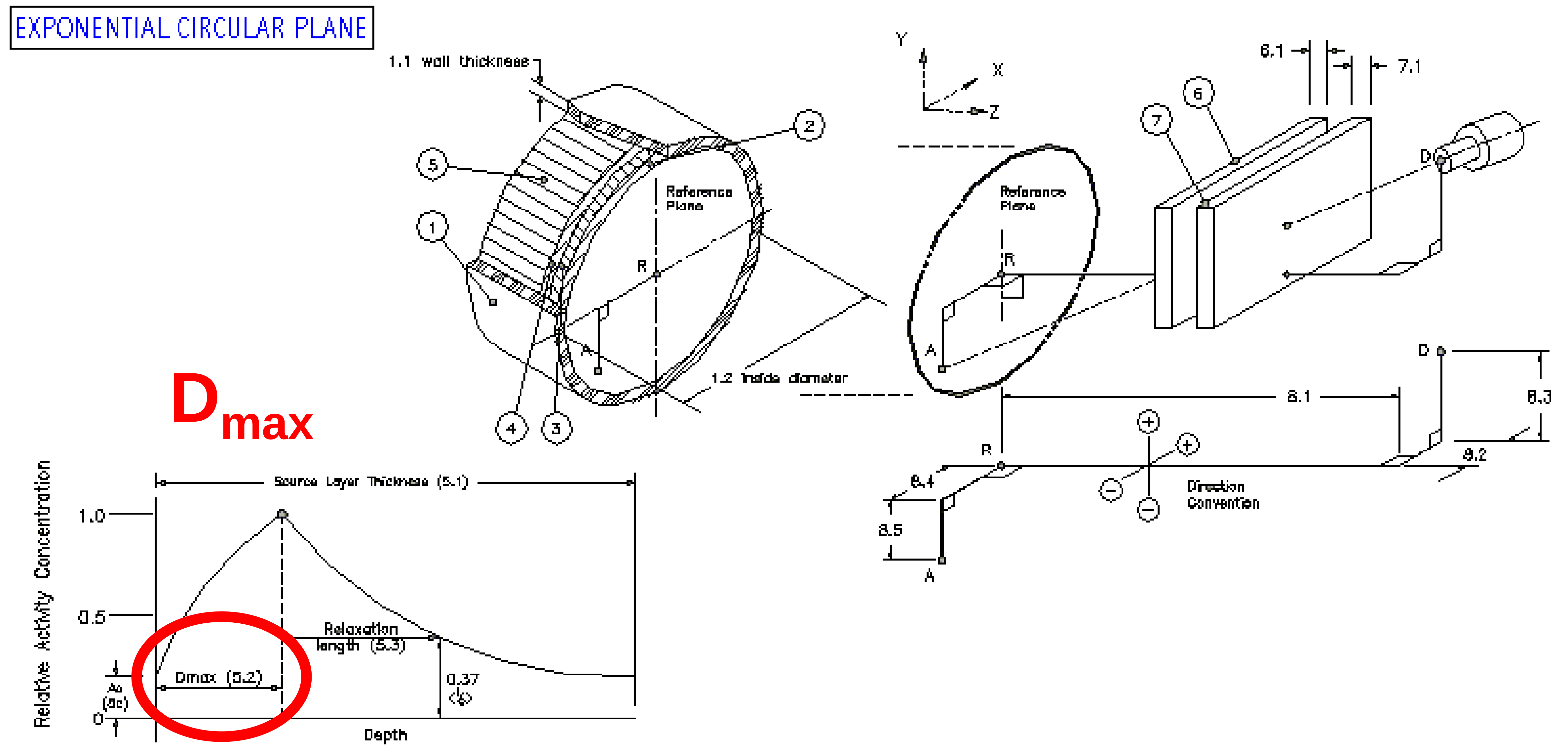
Curve: ● Dual ○ Linear ○ Empirical ○ Interpolated
Scale: ● Linear ○ Log
Order of low energy poly:
Order of the polynomial: 5
Peak: ☐

Datasource: C:\GENIE2K\CAMFILES\NBSSTD.CNF
ln(Eff) = -1.680e+002 + 1.127e+002*ln(E) - 2.998e+001*ln(E)^2 + 3.828e+000*ln(E)^3 - 2.335e-001*ln(E)^4 + 5.312e-003*ln(E)^5

Homogenous distribution - ISOCS

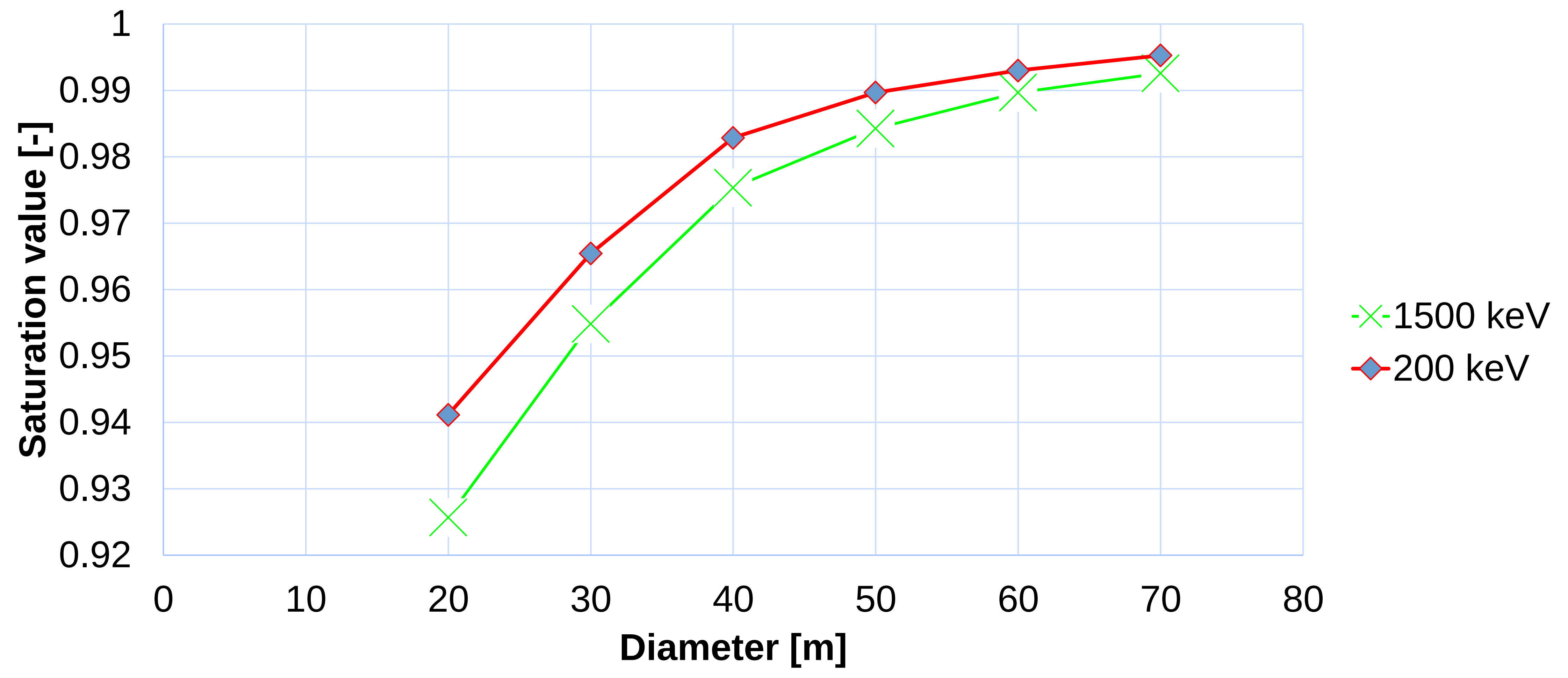


Exponential Distribution - ISOCS



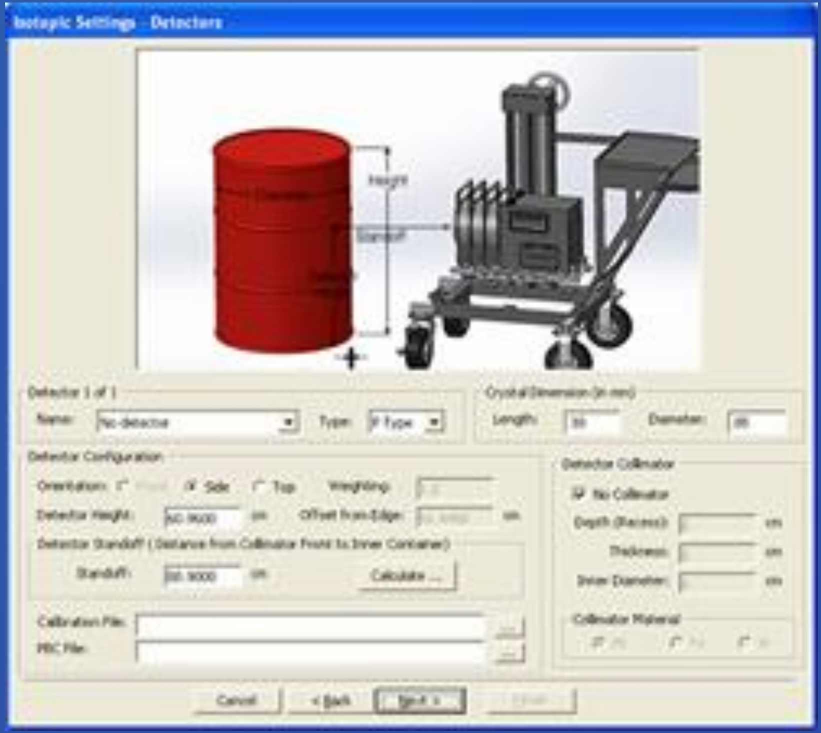
D_{max}

Homogenous distribution- ISOCS

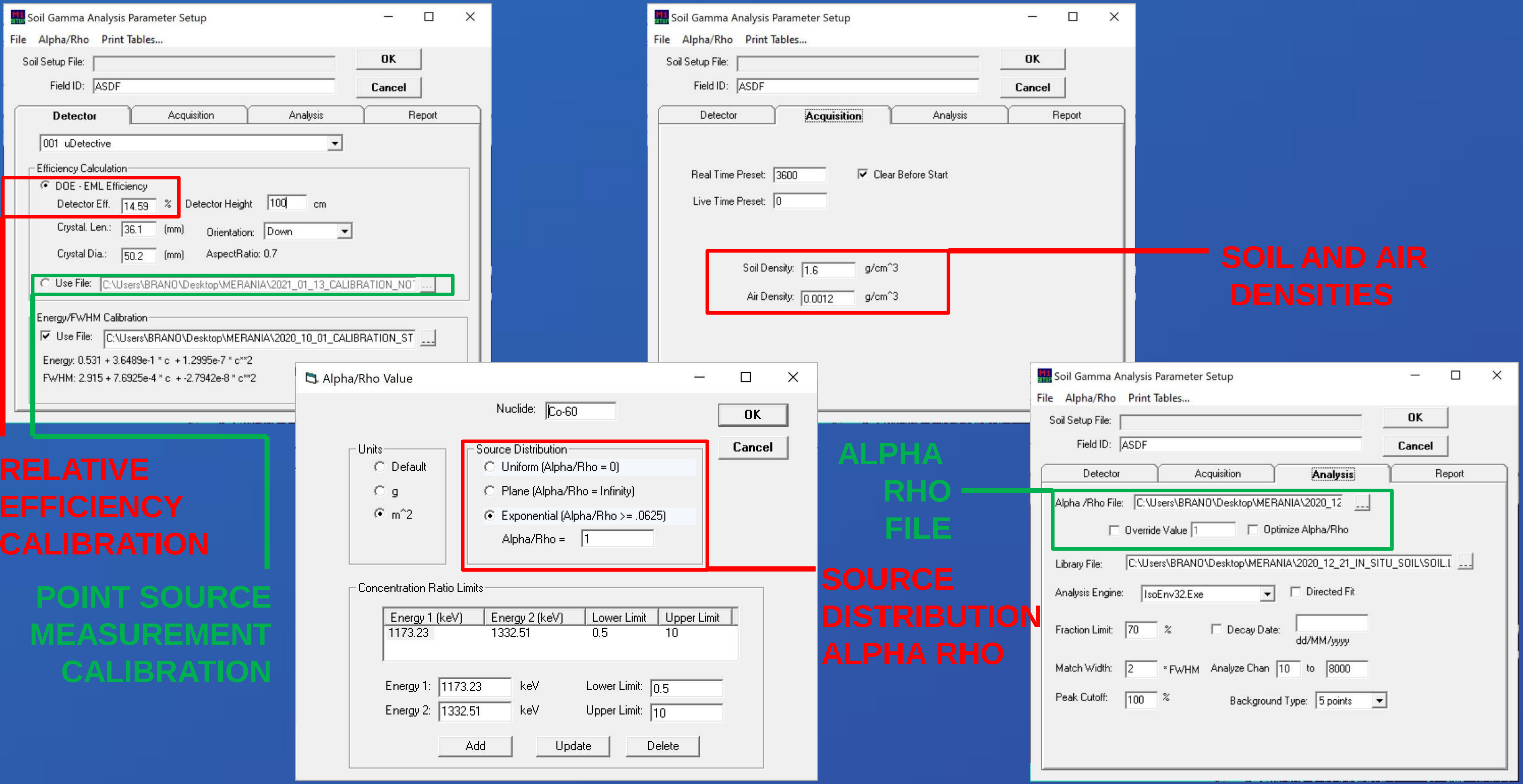


ISOTOPIC

- SW for measuring wide-area contamination of soils and surfaces
- Isotopic Supervisor (for measurement definition)
- Isotopic Operator (for analysis and reporting)
- Geometry Composer (a tool for measurement geometry definition)
- **Two ways of efficiency calibration**
  - DOE/EML – Helfer and Miller estimation
  - Point Source measurement



ISOTOPIC



Soil Setup File:

Field ID: ASDF

Detector

001 uDetective

Efficiency Calculation

● DOE - EML Efficiency

Detector Eff. 14.59 %

Detector Height 100 cm

Crystal Len.: 36.1 (mm)

Orientation: Down

Crystal Dia.: 50.2 (mm)

AspectRatio: 0.7

○ Use File: C:\Users\BRANO\Desktop\MERANIA\2021_01_13_CALIBRATION_NO

Energy/FWHM Calibration

☑ Use File: C:\Users\BRANO\Desktop\MERANIA\2020_10_01_CALIBRATION_ST

Energy: 0.531 + 3.6489e-1 * c + 1.2995e-7 * c**2

FWHM: 2.915 + 7.6925e-4 * c + -2.7942e-8 * c**2

Acquisition

Real Time Preset: 3600

☑ Clear Before Start

Live Time Preset: 0

Soil Density: 1.6 g/cm^3

Air Density: 0.0012 g/cm^3

Alpha/Rho Value

Nuclide: Co-60

Units

○ Default

○ g

● m^2

Source Distribution

○ Uniform (Alpha/Rho = 0)

○ Plane (Alpha/Rho = Infinity)

● Exponential (Alpha/Rho >= .0625)

Alpha/Rho = 1

Concentration Ratio Limits

Energy 1 (keV)	Energy 2 (keV)	Lower Limit	Upper Limit
1173.23	1332.51	0.5	10

Energy 1: 1173.23 keV

Lower Limit: 0.5

Energy 2: 1332.51 keV

Upper Limit: 10

Analysis

Alpha /Rho File: C:\Users\BRANO\Desktop\MERANIA\2020_12

☐ Override Value 1

☐ Optimize Alpha/Rho

Library File: C:\Users\BRANO\Desktop\MERANIA\2020_12_21_IN_SITU_SOIL\SOIL.L

Analysis Engine: IsoEnv32.Exe

☐ Directed Fit

Fraction Limit: 70 %

☐ Decay Date: dd/MM/yyyy

Match Width: 2 * FWHM

Analyze Chan 10 to 8000

Peak Cutoff: 100 %

Background Type: 5 points

SOIL AND AIR DENSITIES

RELATIVE EFFICIENCY CALIBRATION

POINT SOURCE MEASUREMENT CALIBRATION

ALPHA RHO FILE

SOURCE DISTRIBUTION ALPHA RHO

Pros & Cons

PROS
FAST MEASUREMENT
NO SAMPLE
FAST RESULTS

CONS
HIGH UNCERTAINTIES
DETECTOR CONTMINATION POSSIBILITY
ACTIVITY DISTRIBUTION DETERMINATION

CASE STUDY – HOMOGENOUS DISTRIBUTION

Example Ac-228

Manual Calibration

Efficiency Calibration Approach

- **Beck, Helfer, Miller**

$$\boldsymbol{\varepsilon(E) = \frac{N_f}{A} = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}}$$

- $\frac{N_0}{\Phi}$ response factor (intrinsic efficiency of the detector)
- $\frac{N_f}{N_0}$ angular correction factor
- $\frac{\Phi}{A}$ geometrical factor (incident flux arriving to the detector per unit inventory of the radionuclide in the soil)

Response factor $\frac{N_0}{\Phi}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

- **Peak counting rate due to a unit primary photon flux density of Energy E incident on the detector along the detector axis (normal to the detector face)**
- Point Sources at distance of 100 cm
- Whole energy region of interest

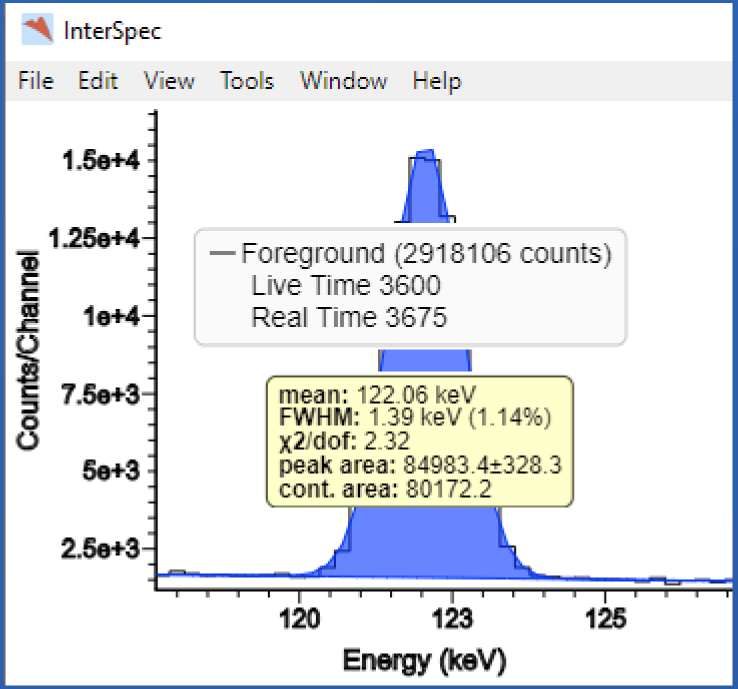
$$\frac{N_0}{\Phi} = \frac{\frac{P_i}{T}}{\frac{Y \times A_{CALIB}}{4\pi r^2}} = \frac{4\pi r^2 \times P_i}{Y \times A \times T}$$

$r\ [m]$	**is the source to detector distance**
$P_i\ [-]$	**is net count in the full energy peak for energy** E
$Y\ [-]$	**is gamma yield per decay for photons of energy** E
$A_{CALIB}[Bq]$	**is activity of point source**
$T\ \ [s]$	**is the measuring time**

Response factor $\frac{N_0}{\Phi}$

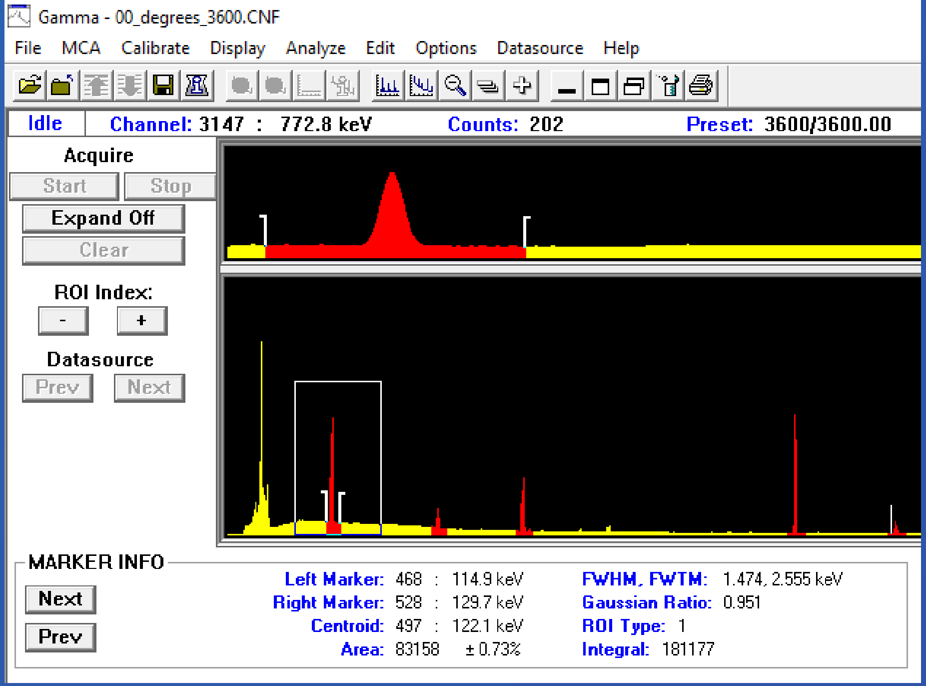
$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

- Any SW
- Peak net Area



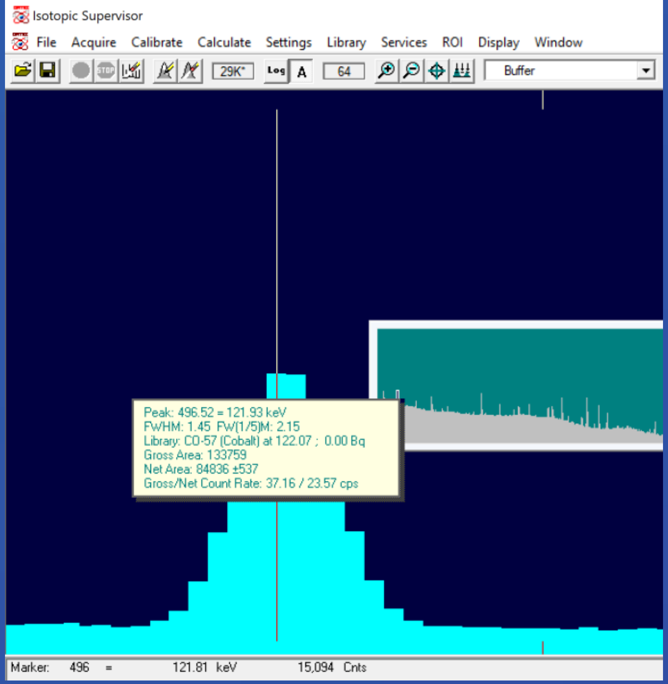
Foreground (2918106 counts)
Live Time 3600
Real Time 3675

mean: 122.06 keV
FWHM: 1.39 keV (1.14%)
χ2/dof: 2.32
peak area: 84983.4±328.3
cont. area: 80172.2



Idle Channel: 3147 : 772.8 keV Counts: 202 Preset: 3600/3600.00

Left Marker: 468 : 114.9 keV
Right Marker: 528 : 129.7 keV
Centroid: 497 : 122.1 keV
Area: 83158 ± 0.73%
FWHM, FWTM: 1.474, 2.555 keV
Gaussian Ratio: 0.951
ROI Type: 1
Integral: 181177



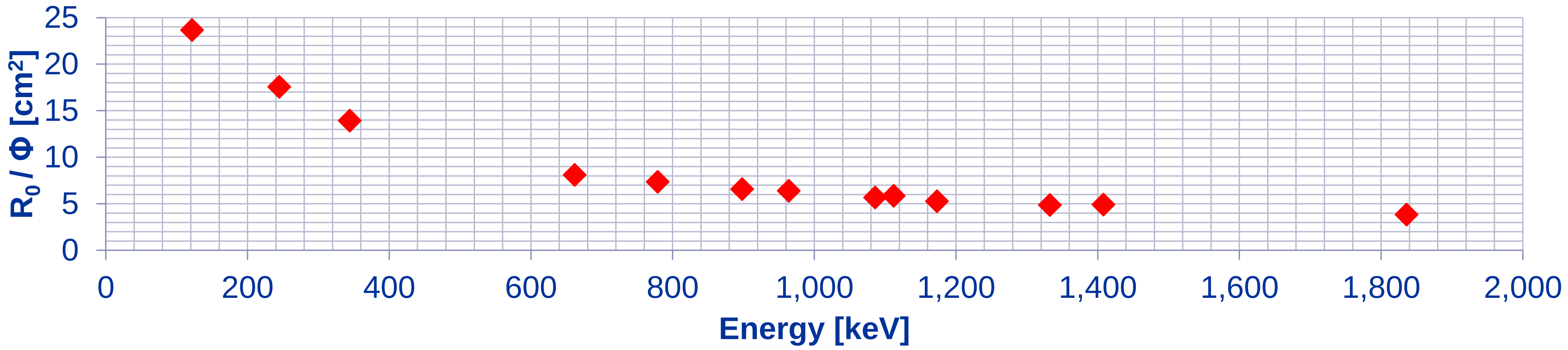
Peak: 496.52 = 121.93 keV
FWHM: 1.45 FW(1/5)M: 2.15
Library: CO-57 (Cobalt) at 122.07 ; 0.00 Bq
Gross Area: 133759
Net Area: 84836 ±537
Gross/Net Count Rate: 37.16 / 23.57 cps

Marker: 496 = 121.81 keV 15,094 Cnts

Response factor $\frac{N_0}{\Phi}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

Energy [keV]	121	244	344	661	778	898	964	1085	1112	1173	1332	1408	1836
Nuclide	152-Eu	152-Eu	152-Eu	137-Cs	152-Eu	Y-88	152-Eu	152-Eu	152-Eu	60-Co	60-Co	152-Eu	Y-88
A [kBq]	450	450	450	591	450	47	450	450	450	417	417	450	47
T [s]	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600	3600
Y[-]	0.284	0.076	0.266	0.850	0.130	0.937	0.145	0.101	0.134	0.999	1.000	0.209	0.993
N [-]	84983	16758	46801	113793	12064	8113	11743	7265	9918	57725	53349	12985	5019
N0 / Φ [cm²]	23.665	17.560	13.925	8.112	7.359	6.569	6.407	5.674	5.851	5.274	4.868	4.927	3.833



Angular correction factor $\frac{N_f}{N_0}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

$$W = \frac{N_f}{N_0} = \frac{\int R(\theta)\Phi(\theta)d\theta}{\int \Phi(\theta)d\theta}$$

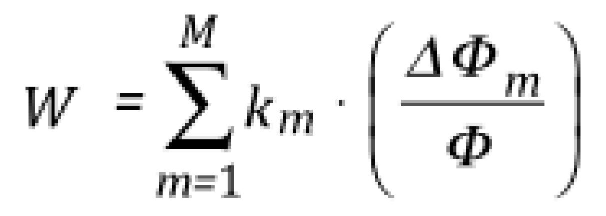
$$R(\theta) = \frac{\frac{P_\theta}{t_\theta}}{\frac{P_0}{t_0}}$$

- It depends on the detector and source distribution in the soil.
- Angular correction factor can be calculated from the measurement according to the equation.
- This factor expresses weighted angular response compared to the normal response

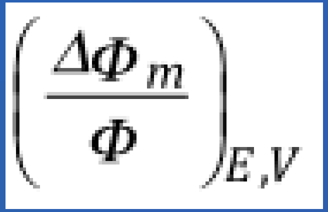
Angular correction factor $\frac{N_f}{N_0}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

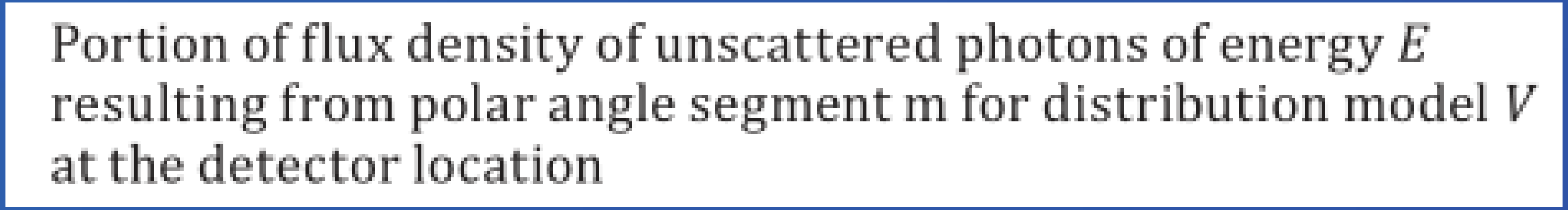
- ISO



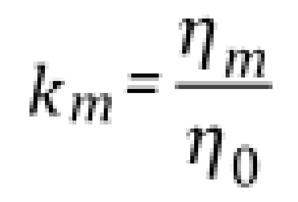
$$W = \sum_{m=1}^{M} k_m \cdot \left(\frac{\Delta\Phi_m}{\Phi}\right)$$



$$\left(\frac{\Delta\Phi_m}{\Phi}\right)_{E,V}$$



Portion of flux density of unscattered photons of energy *E* resulting from polar angle segment m for distribution model *V* at the detector location

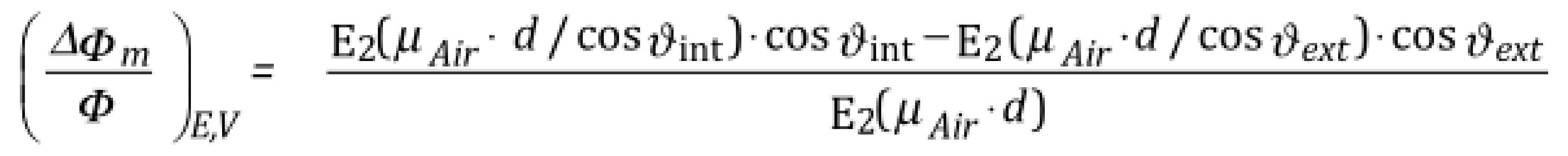


$$k_m = \frac{\eta_m}{\eta_0}$$

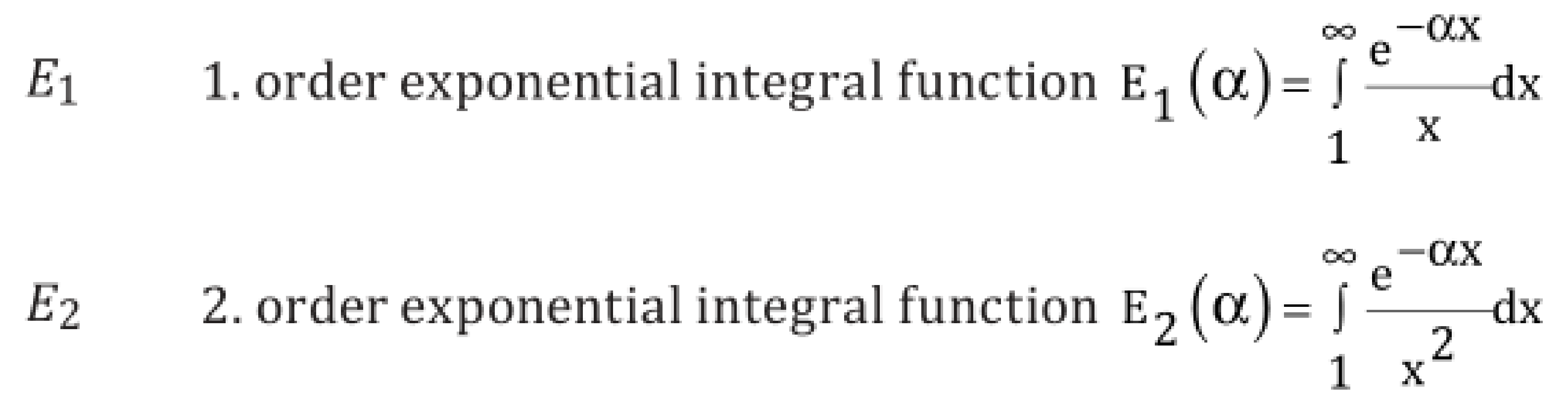
η_m	Cross section of the detector for photons from the polar segment, *m*	m^2
η_0	Intrinsic efficiency	m^2

Angular correction factor $\frac{N_f}{N_0}$ $\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$

- **HOMOGENOUS DISTRIBUTION**



$$\left(\frac{\Delta\Phi_m}{\Phi}\right)_{E,V} = \frac{E_2(\mu_{Air} \cdot d / \cos\vartheta_{int}) \cdot \cos\vartheta_{int} - E_2(\mu_{Air} \cdot d / \cos\vartheta_{ext}) \cdot \cos\vartheta_{ext}}{E_2(\mu_{Air} \cdot d)}$$

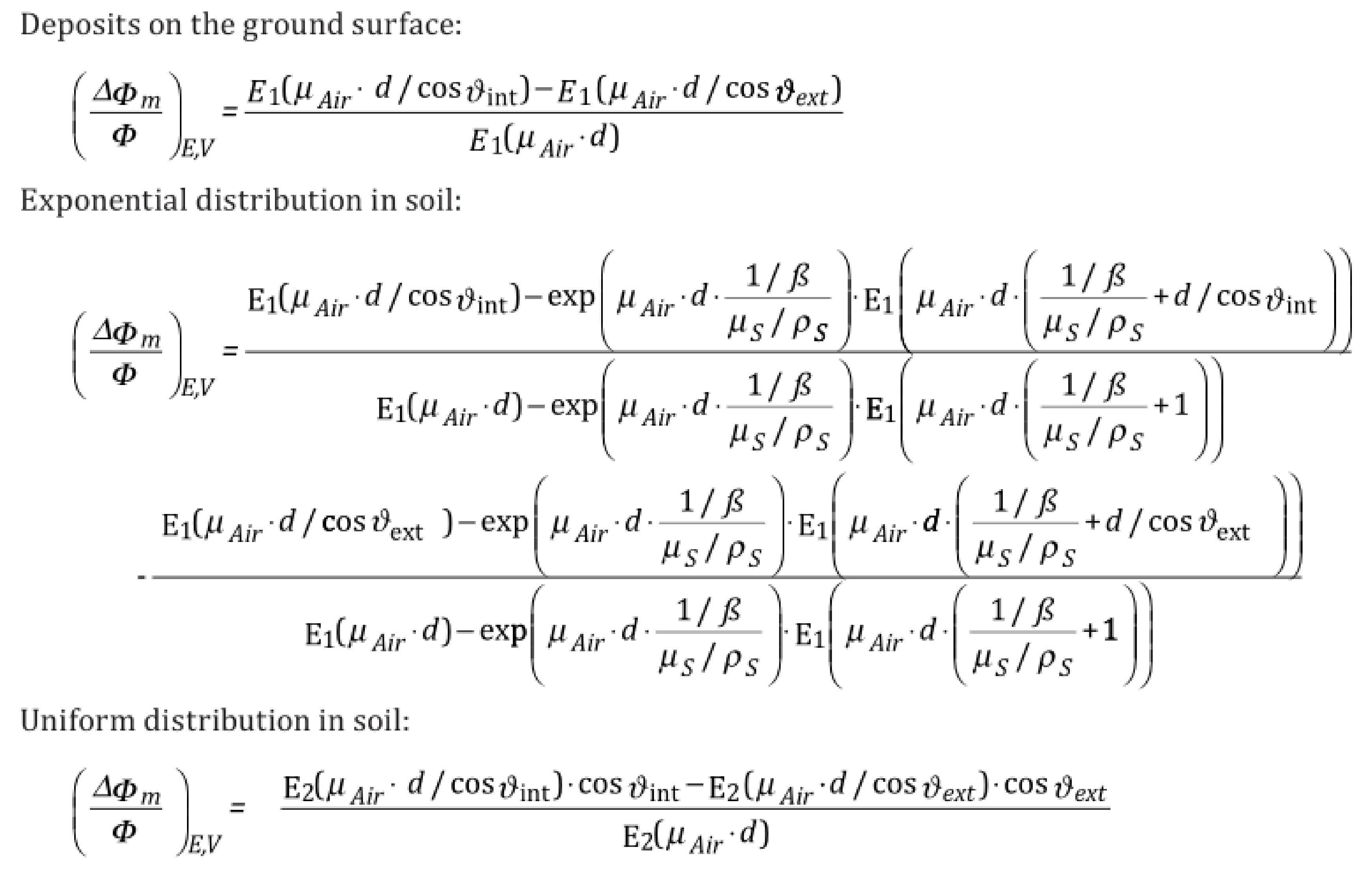


E_1 1. order exponential integral function $E_1(\alpha) = \int_1^\infty \frac{e^{-\alpha x}}{x} dx$

E_2 2. order exponential integral function $E_2(\alpha) = \int_1^\infty \frac{e^{-\alpha x}}{x^2} dx$

Angular correction factor $\frac{N_f}{N_0}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$



Deposits on the ground surface:

$$\left(\frac{\Delta\Phi_m}{\Phi}\right)_{E,V} = \frac{E_1(\mu_{Air}\cdot d/\cos\vartheta_{int}) - E_1(\mu_{Air}\cdot d/\cos\vartheta_{ext})}{E_1(\mu_{Air}\cdot d)}$$

Exponential distribution in soil:

$$\left(\frac{\Delta\Phi_m}{\Phi}\right)_{E,V} = \frac{\mathrm{E}_1(\mu_{Air}\cdot d/\cos\vartheta_{int}) - \exp\left(\mu_{Air}\cdot d\cdot\frac{1/\text{ß}}{\mu_S/\rho_S}\right)\cdot\mathrm{E}_1\left(\mu_{Air}\cdot d\cdot\left(\frac{1/\text{ß}}{\mu_S/\rho_S}+d/\cos\vartheta_{int}\right)\right)}{\mathrm{E}_1(\mu_{Air}\cdot d) - \exp\left(\mu_{Air}\cdot d\cdot\frac{1/\text{ß}}{\mu_S/\rho_S}\right)\cdot\mathrm{E}_1\left(\mu_{Air}\cdot d\cdot\left(\frac{1/\text{ß}}{\mu_S/\rho_S}+1\right)\right)}$$

$$- \frac{\mathrm{E}_1(\mu_{Air}\cdot d/\cos\vartheta_{ext}) - \exp\left(\mu_{Air}\cdot d\cdot\frac{1/\text{ß}}{\mu_S/\rho_S}\right)\cdot\mathrm{E}_1\left(\mu_{Air}\cdot d\cdot\left(\frac{1/\text{ß}}{\mu_S/\rho_S}+d/\cos\vartheta_{ext}\right)\right)}{\mathrm{E}_1(\mu_{Air}\cdot d) - \exp\left(\mu_{Air}\cdot d\cdot\frac{1/\text{ß}}{\mu_S/\rho_S}\right)\cdot\mathrm{E}_1\left(\mu_{Air}\cdot d\cdot\left(\frac{1/\text{ß}}{\mu_S/\rho_S}+1\right)\right)}$$

Uniform distribution in soil:

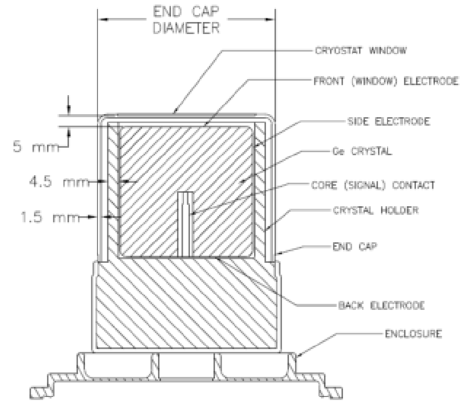
$$\left(\frac{\Delta\Phi_m}{\Phi}\right)_{E,V} = \frac{\mathrm{E}_2(\mu_{Air}\cdot d/\cos\vartheta_{int})\cdot\cos\vartheta_{int} - \mathrm{E}_2(\mu_{Air}\cdot d/\cos\vartheta_{ext})\cdot\cos\vartheta_{ext}}{\mathrm{E}_2(\mu_{Air}\cdot d)}$$

Angular correction factor $\frac{N_f}{N_0}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

- not so simple calculation…..
- Hellfer and Miller tables, Isotopic SW manual, etc…..
  - Angular Correction Factor, (Nf /N0), Downward-Facing Detector, Plane Source Distribution (α/ρ =0).

Energy	L/D								
[MeV]	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3
0.3	0.81	0.82	0.83	0.86	0.91	0.99	1.08	1.18	1.31
0.5	0.84	0.85	0.85	0.88	0.93	0.99	1.06	1.14	1.25
0.7	0.86	0.86	0.87	0.91	0.93	0.98	1.05	1.12	1.21
1.0	0.88	0.88	0.89	0.91	0.94	0.98	1.03	1.10	1.18
1.5	0.91	0.91	0.91	0.92	0.94	0.97	1.02	1.07	1.13
2.0	0.92	0.92	0.93	0.93	0.94	0.96	1.00	1.05	1.10
2.5	0.94	0.94	0.94	0.94	0.95	0.96	0.99	1.03	1.07

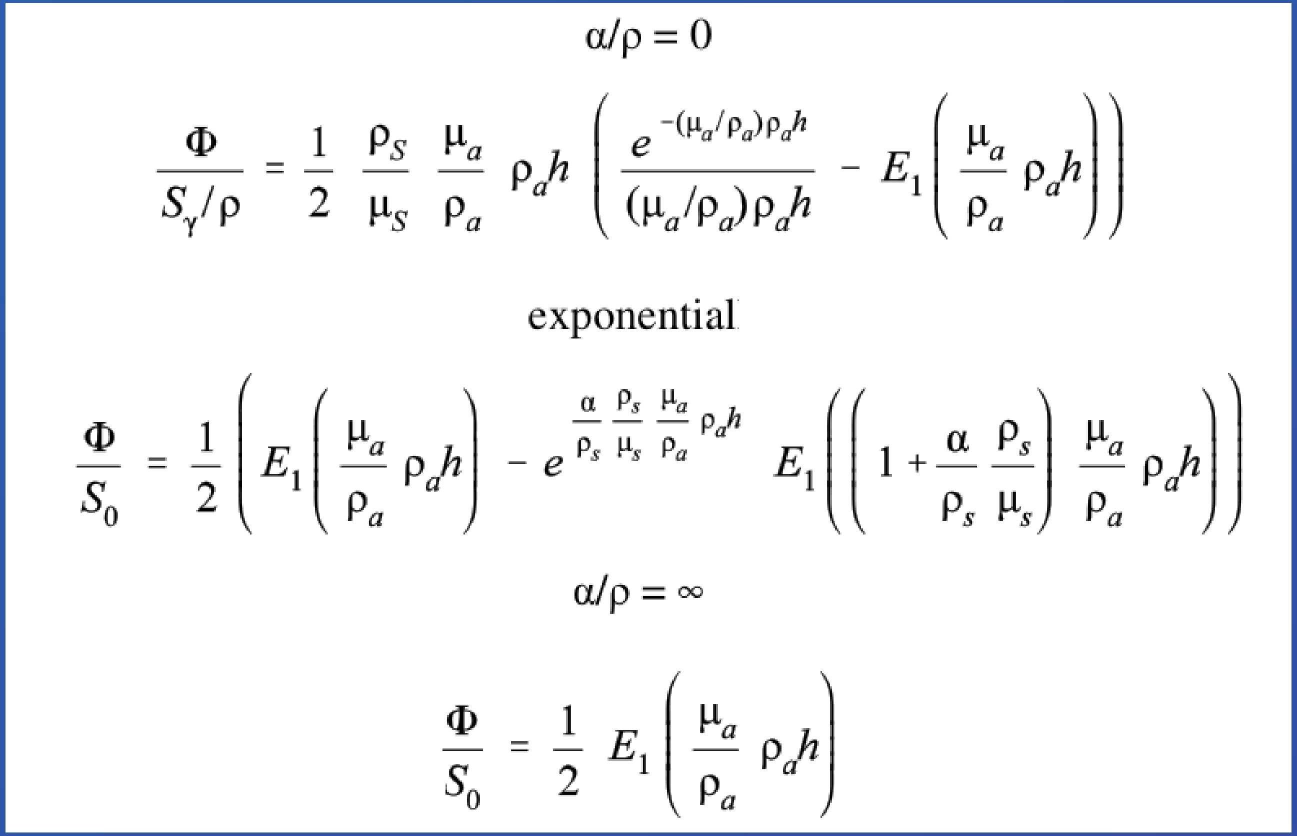


Ge Crystal Diameter	**60±2**	**mm**
Ge Crystal Thickness	**60±2**	**mm**
Core Hole Diameter	**7.1**	**mm**
Core Hole Depth	**30**	**mm**
Front (Window) Electrode Dead Layer	*****	**mm (typ 0.003 mm)**
Side Electrode Dead Layer	*****	**mm (typ .5mm)**
Back Electrode Dead Layer	*****	**mm (typ .5mm)**

Geometrical factor $\frac{\Phi}{A}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

- The last parameter Φ/A is incident flux at that energy arriving at the detector per unit inventory or concentration of the nuclide in the soil. It is not dependent on detector, but it is function of soil density, soil composition, air attenuation and the source distribution in the soil.



$$\alpha/\rho = 0$$

$$\frac{\Phi}{S_\gamma/\rho} = \frac{1}{2}\,\frac{\rho_S}{\mu_S}\,\frac{\mu_a}{\rho_a}\,\rho_a h\left(\frac{e^{-(\mu_a/\rho_a)\rho_a h}}{(\mu_a/\rho_a)\rho_a h} - E_1\left(\frac{\mu_a}{\rho_a}\,\rho_a h\right)\right)$$

exponential

$$\frac{\Phi}{S_0} = \frac{1}{2}\left(E_1\left(\frac{\mu_a}{\rho_a}\,\rho_a h\right) - e^{\frac{\alpha}{\rho_s}\frac{\rho_s}{\mu_s}\frac{\mu_a}{\rho_a}\rho_a h}\,E_1\left(\left(1 + \frac{\alpha}{\rho_s}\,\frac{\rho_s}{\mu_s}\right)\frac{\mu_a}{\rho_a}\,\rho_a h\right)\right)$$

$$\alpha/\rho = \infty$$

$$\frac{\Phi}{S_0} = \frac{1}{2}\,E_1\left(\frac{\mu_a}{\rho_a}\,\rho_a h\right)$$

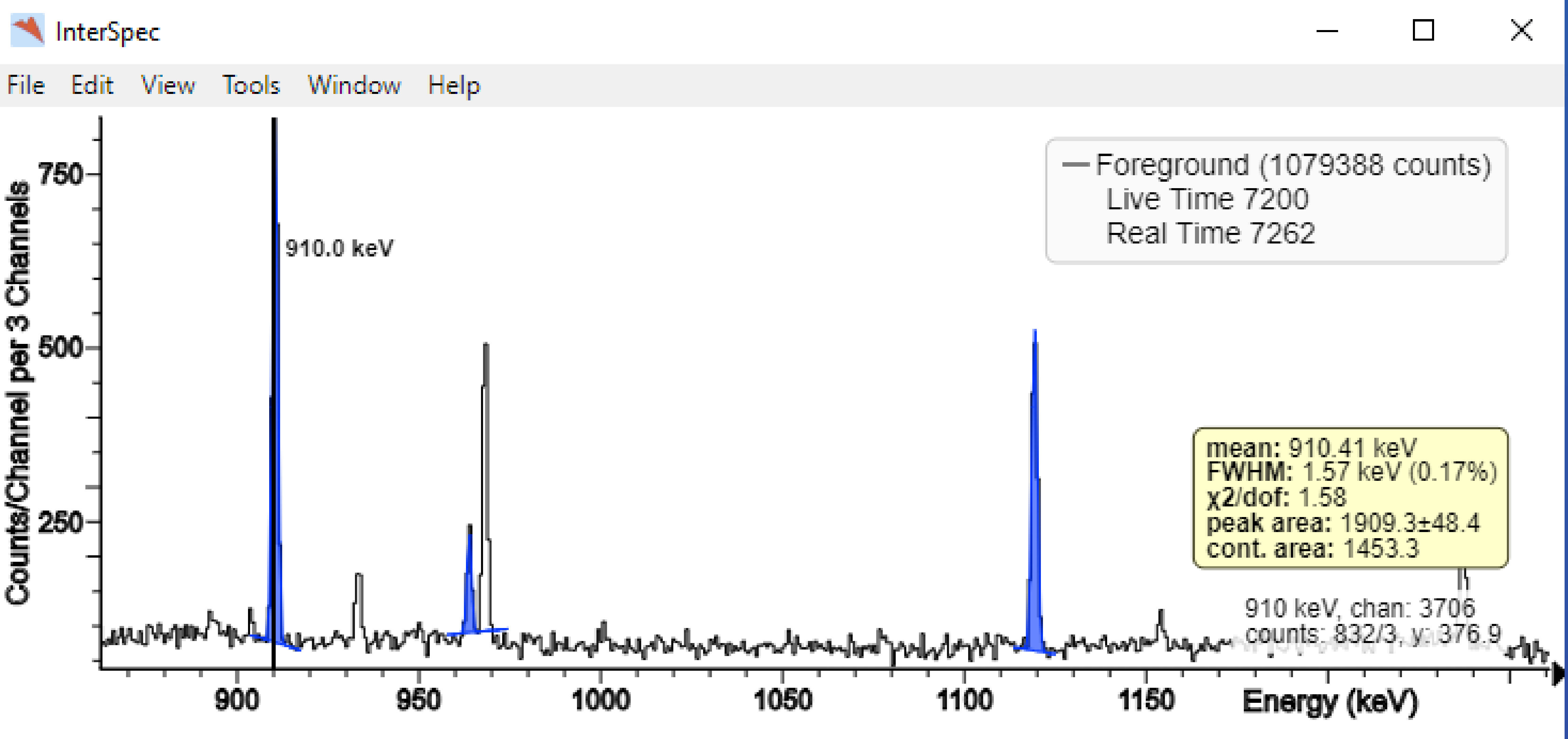
Geometrical factor $\frac{\Phi}{A}$

$$\varepsilon(E) = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

- Beck established the following table for unscattered flux one meter above the ground for various energies and α/ρ values.

[(cm^{-2} s^{-1}) / Bq g^{-1})] for α/ρ = 0 (uniform profile, natural emitters)							
[(cm^{-2} s^{-1}) / Bq cm^{-1})] for α/ρ > 0 (exponential profile, fallout)							
Energy	α/ρ						
[MeV]	**0**	0.06	0.206	0.312	0.625	6.25	∞
0.050	**1.4403**	0.0816	0.2245	0.3049	0.4748	1.147	1.58
0.100	**2.1140**	0.1458	0.3627	0.4708	0.6786	1.359	1.71
0.150	**3.3264**	0.1702	0.4103	0.5261	0.7438	1.427	1.78
0.200	**3.9056**	0.1843	0.4550	0.5770	0.8020	1.483	1.80
0.250	**4.0640**	0.2008	0.4697	0.5910	0.8185	1.506	1.86
0.364	**4.7184**	0.2268	0.5158	0.6429	0.8775	1.578	1.93
0.500	**5.3904**	0.2519	0.5595	0.6918	0.9334	1.650	2.00
0.662	**6.1456**	0.2788	0.6041	0.7412	0.9889	1.719	2.05
0.750	**6.5312**	0.2919	0.6257	0.7649	1.0150	1.752	2.08
1.000	**7.5280**	0.3245	0.6769	0.8209	1.0770	1.830	2.15
1.173	**8.1472**	0.3437	0.7067	0.8531	1.1130	1.874	2.19
1.250	**8.4384**	0.3523	0.7198	0.8675	1.1290	1.895	2.21
1.333	**8.7504**	0.3617	0.7336	0.8826	1.1450	1.914	2.22
1.460	**9.1472**	0.3731	0.7511	0.9011	1.1660	1.941	2.25
1.765	**10.0910**	0.3997	0.7897	0.9428	1.2110	1.997	2.29
2.004	**10.8180**	0.4188	0.8173	0.9725	1.2430	2.036	2.33
2.250	**11.3970**	0.4357	0.8410	0.9982	1.2710	2.071	2.36
2.500	**12.1700**	0.4536	0.8667	1.0250	1.3000	2.105	2.39

Peak Net Area – ^{228}Ac



Foreground (1079388 counts)
Live Time 7200
Real Time 7262

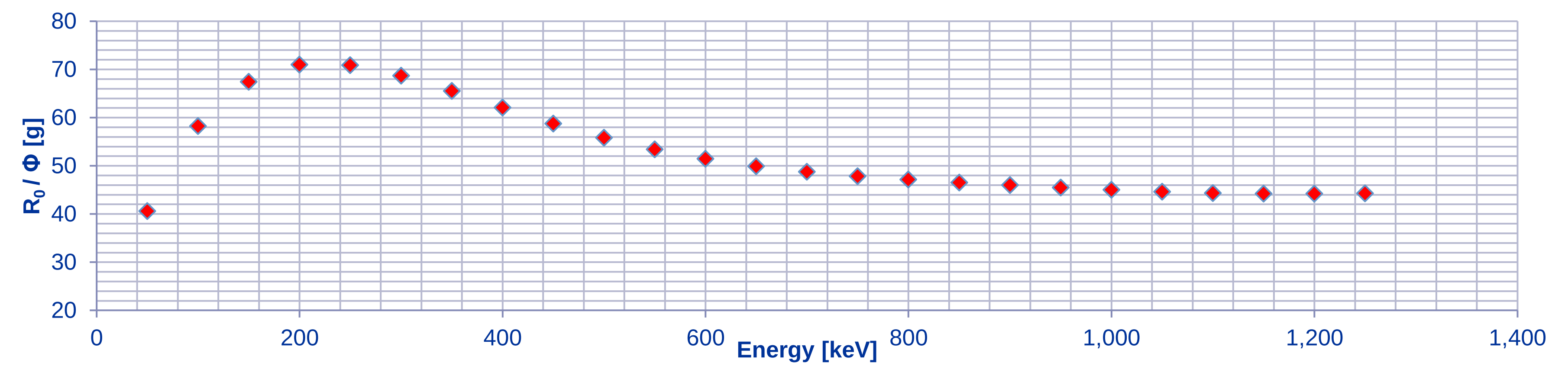
mean: 910.41 keV
FWHM: 1.57 keV (0.17%)
$\chi2$/dof: 1.58
peak area: 1909.3±48.4
cont. area: 1453.3

910 keV, chan: 3706
counts: 832/3, y: 376.9

Efficiency Calibration Approach – ^{228}Ac

$$\varepsilon(E) = \frac{N_f}{A} = \frac{N_0}{\Phi} \times \frac{N_f}{N_0} \times \frac{\Phi}{A}$$

Energy [keV]	338.3	911.2	964.8	969.0
N_0 / Φ [cm^2]	14.10	6.62	6.35	6.33
N_f/N_0 [-]	0.99	0.98	0.98	0.98
Φ / A [cm^{-2} g]	4.75	7.07	7.29	7.31
N_0/A [g]	**66.29**	**45.86**	**45.33**	**45.30**



Results – ^{228}Ac

$$A = \frac{N}{T * Y * \boldsymbol{\varepsilon}}$$

Energy [keV]	338.3	911.2	964.8	969.0
Y	0.114	0.262	0.049	0.159
ε [g]	66.29	45.86	45.33	45.30
Peak Net Area	1093	1909	310	1211
T [s]	7200	7200	7200	7200
A [Bq kg-1]	**20.09**	**22.07**	**19.03**	**23.35**

CASE STUDY – HOMOGENOUS – RESULTS
Example Ac-228

DETECTOR	METHOD	ACTIVITY
AEGIS	ISOCS	26.15 ± 0.89 Bq/kg
AEGIS	ISOTOPIC PS	23.92 ± 2.25 Bq/kg
AEGIS	ISOTOPIC %	20.87 ± 0.94 Bq/kg
AEGIS	**MANUAL**	**21.14 ± 1.68 Bq/kg**
LAB	LabSOCS	21.30 ± 0.40 Bq/kg

Thank you for the attention!

Literature