Challenges in Regulating NORM for proper Worker Protection – Prior Radiological Characterisation and Realistic Dose Assessment

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ΕΕΑΕ ΕΛΛΗΝΙΚΗ ΕΠΙΤΡΟΠΗ ΑΤΟΜΙΚΗΣ ΕΝΕΡΓΕΙΑΣ
GREEK ATOMIC ENERGY COMMISSION

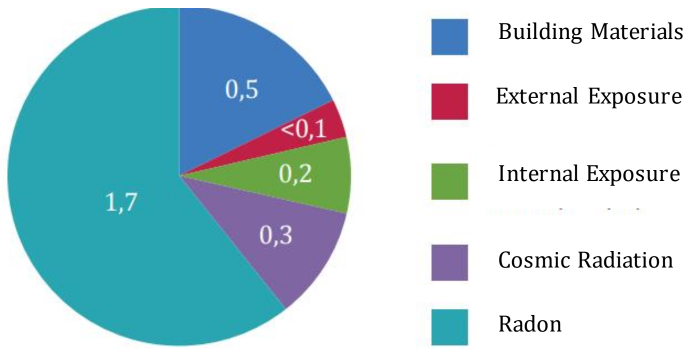
Environmental Radioactivity –
Mean Annual Effective Dose (mSv/έτος)

Natural radiation is a major contributor to an individual annual dose due to ionizing radiation.

Main pathways:

- Radon within the buildings
- γ- radiation due to building materials
- Cosmic radiation
- External exposure (e.g. soil)
- Internal exposure (e.g. ingestion)

Mean individual annual effective dose due to the environment



η περιφέρεια στο επίκεντρο της ανάπτυξης

Με τη συγχρηματοδότηση της Ελλάδας και της Ευρωπαϊκής Ένωσης - Ευρωπαϊκό Ταμείο Περιφερειακής Ανάπτυξης (ΕΤΠΑ), στο πλαίσιο του Ε.Π. Ανταγωνιστικότητα και Επιχειρηματικότητα (ΕΠΑΝ ΙΙ) και των Π.Ε.Π. Αττικής, Π.Ε.Π. Μακεδονίας - Θράκης

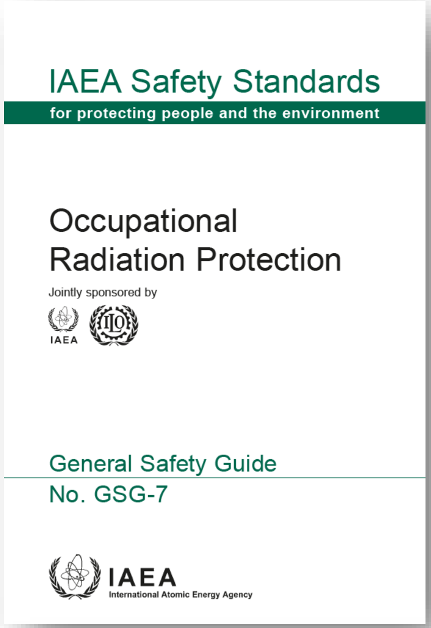
Industries involving NORM

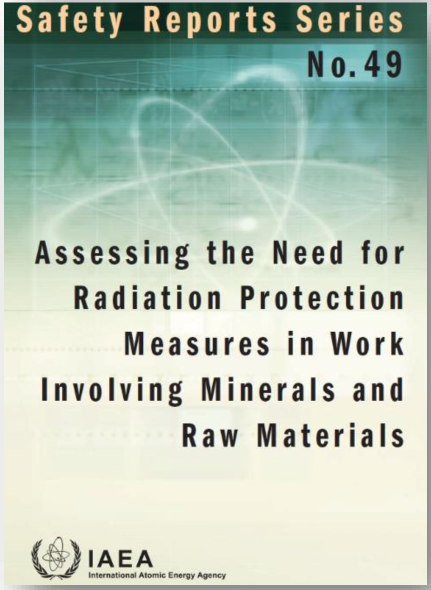
- Industries that process natural radioactive materials extracted from the earth's crust can expose workers to radiation while the corresponding releases to the environment, might also affect public.

- Industrial activities of interest could include processing and storage of NORM or could produce waste that contain natural radionuclides.

IAEA documents related to dose assessments in NORM industries

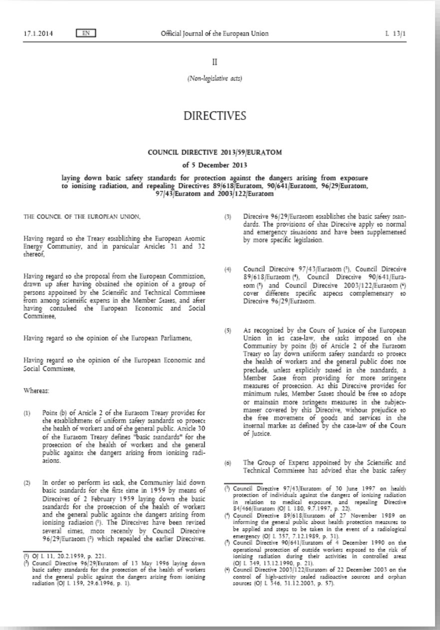
- GSG-7 refers to IAEA SR-49 for dose estimates in a NORM context
- Most relevant exposure pathways in NORM industries
  - ✓ External exposure to gamma radiation
  - ✓ Internal exposure via the inhalation to dust
  - ✓ Internal exposure via the inhalation of radon
- For various NORM industries, SR-49 established a relationship between effective dose and the activity concentration of the materials involved





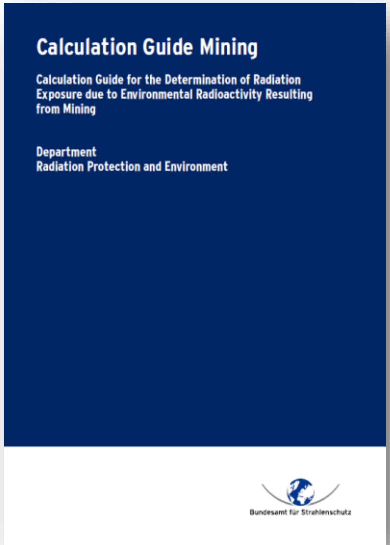
Exposure of workers due to natural sources
Paras 3.159–3.181 and Appendix I

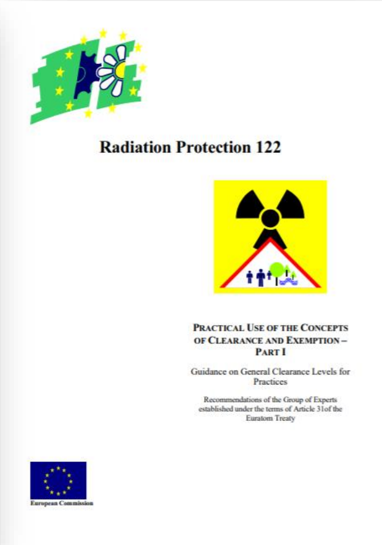
EC documents related to dose assessments in NORM industries

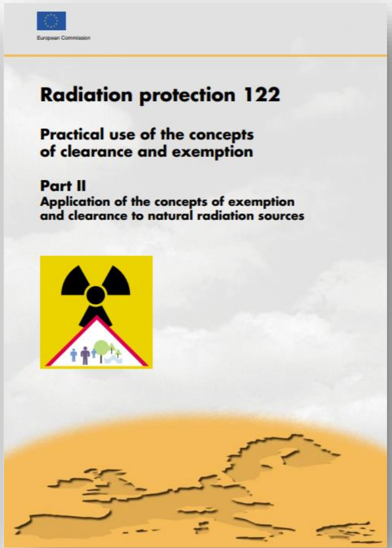


- Council Directive 2013/59/Euratom
- Radiation Protection 122 *(ref. to the previous BSSS)*
  - ✓ Practical use of the concept of clearance and exception
  - ✓ Application of the concepts of exemption and clearance to natural radiation sources

BfS - **Calculation Guide for the Determination of Radiation Exposure due to Environmental Radioactivity Resulting from Mining**

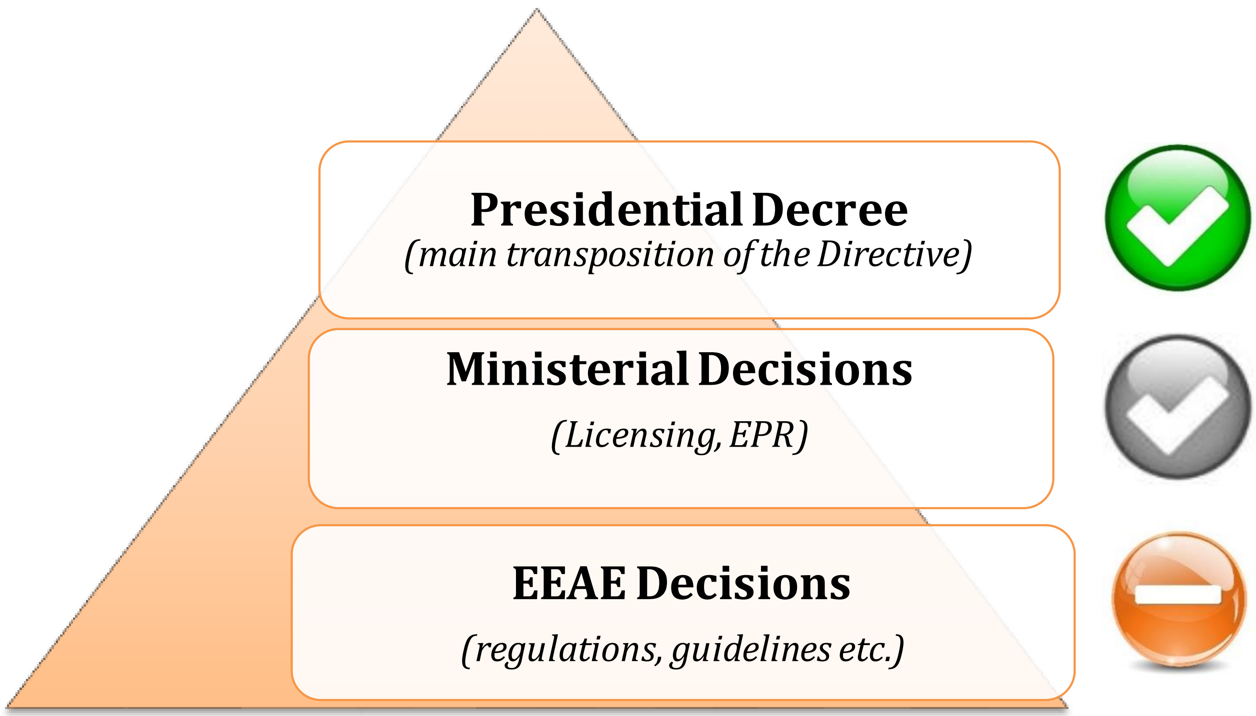






National legislative framework (Greece)

Radiation Protection Regulations



National legislative framework (Greece)

Article 23 – Annex VI:

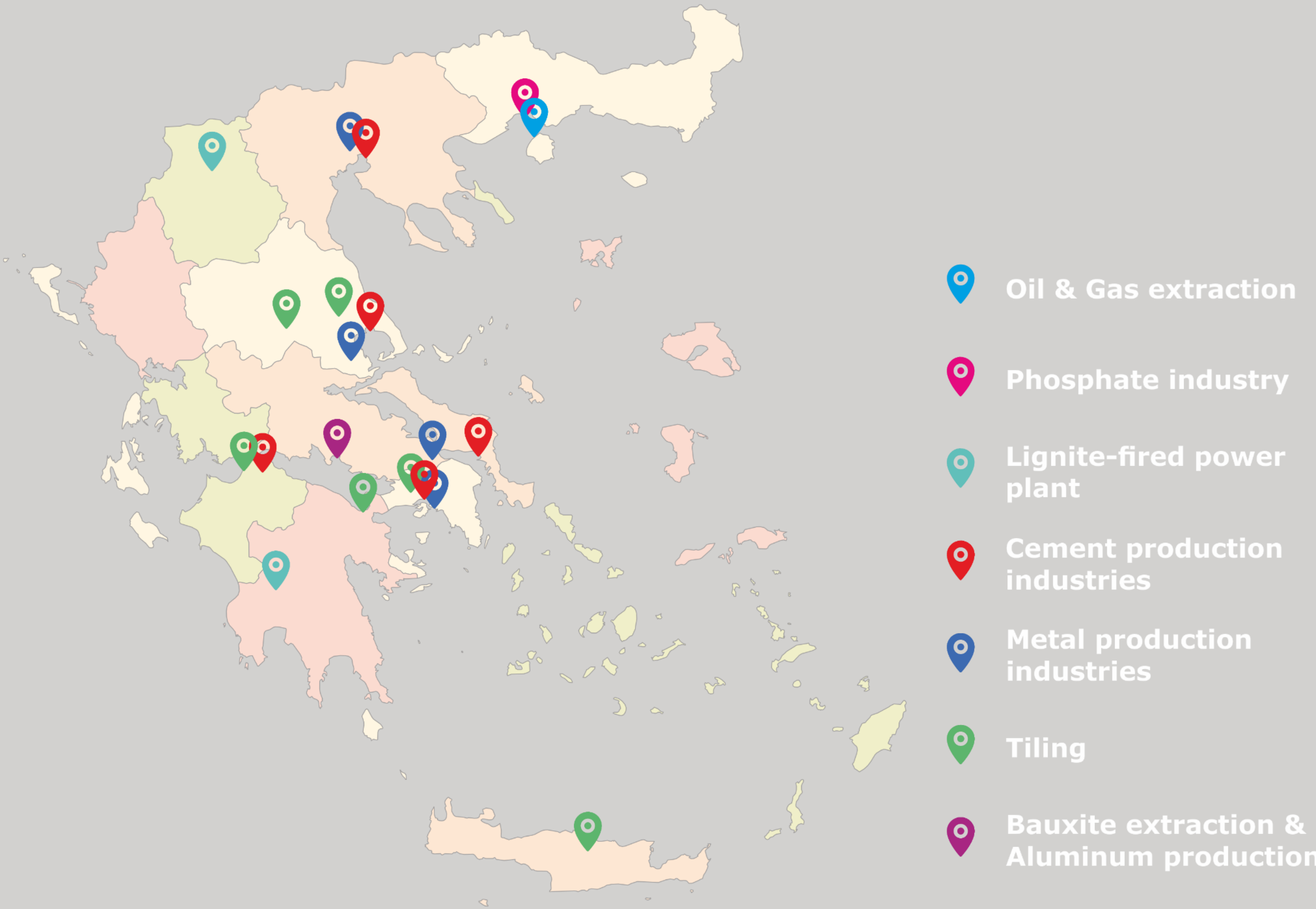
Identification of practices involving naturally-occurring radioactive material

Industrial fields / sectors:

1. Extraction of rare earths from monazite
2. Production of thorium compounds and manufacture of thorium-containing products
3. Processing of niobium/tantalum ore
4. Oil and gas production
5. Geothermal energy production
6. TiO_2 pigment production
7. Thermal phosphorus production
8. Zircon and zirconium industry
9. Production of phosphate fertilizers
10. Cement production, maintenance of clinker ovens
11. Coal-fired power plants, maintenance of boilers
12. Phosphoric acid production,
13. Primary iron production,
14. Tin/lead/copper smelting,
15. Ground water filtration facilities,
16. Mining of ores other than uranium ore.
17. Extraction and processing of bauxite and aluminum production
18. Use of healing natural resources (eg. spa)
19. Tunneling in rock formations rich in uranium and / or thorium




NORM industries distributed in Greece



National legislative framework (Greece) – Regulatory control

- **Article 24:** Graded approach to regulatory control
  - ✓ Notification / Registration ~~/ Licensing~~

- **Articles 26, 30:** Release from regulatory control

Naturally occurring radionuclides:

Values for exemption or clearance for naturally occurring radionuclides in solid materials in secular equilibrium with their progeny:

from the ^{238}U series	1000 Bq/kg
From the ^{232}Th series	1000 Bq/kg
^{40}K	10000 Bq/kg

The exemption criteria, **where there is concern that a practice may lead to the presence of NORM in water** liable to affect the **quality of drinking water** supplies or affect any other exposure pathways, so as to be of concern from a radiation protection point of view, the competent authority may require that **the practice be subject to notification**.

<u>Transitional provisions</u>

Industries that are using NORM:

- Characterization of their material that may contain NORM
- Identify their activities that might cause the presence of NORM in the water
- Inform the Regulatory Body on their participation in activities such as incorporation into building materials of residues from industries processing naturally-occurring radioactive material

Requirements on dose assessment of workplaces involving NORM

Notification / registration

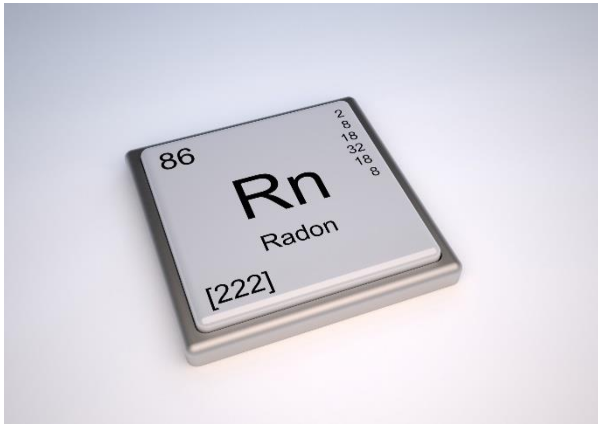
- If workplace is on List **a dose estimate** has to be carried out prior to commencing the work by a **Qualified Expert** (i.e. Radiation Protection Expert

  - ✓ Planned radiation protection measures
  - ✓ Proof of availability of state of the art equipment and procedures to comply with the planned protection measures
  - ✓ Proof of availability of **radiation protection officers and their qualification**
  - ✓ Proof of adequate **qualification and training** of affected workers

No One Size Fits All Solution

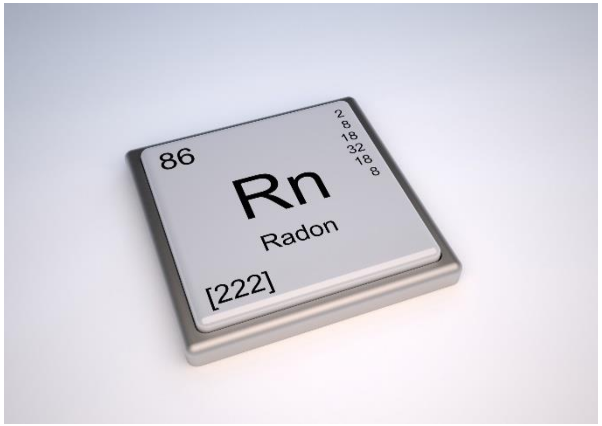
Radon at workplaces: existing exposure situation

- Rn-222 at indoor workplaces is regulated under the new Law
  - ✓ Reference value of 300 Bq/m^3
- Requirement to measure Rn concentration, if…
  - ✓ Workplace is on ground floor or basement in a **"radon-prone area"**
  - ✓ Underground mines, caves and museum mines
  - ✓ Radon spas
- Water supply and treatment facilities
- Other workplaces may be subject to regulation if competent authority deems it necessary (indication of increased exposure to radon)



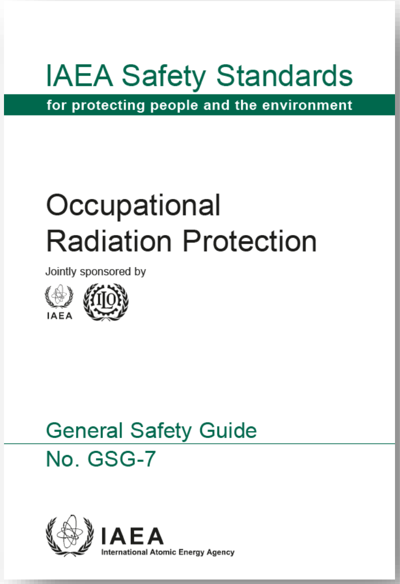
Requirements to assess radon at workplaces

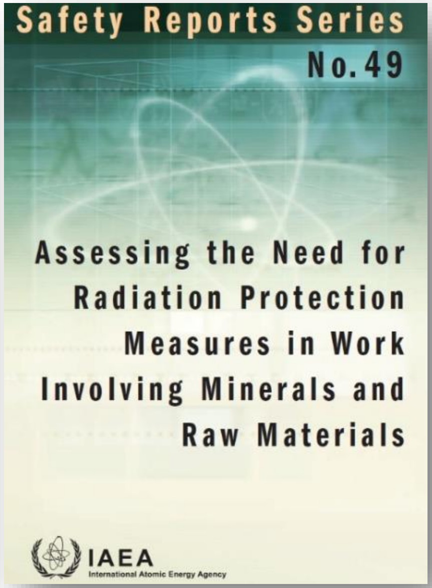
- If workplace measurement shows annual average radon concentration > 300 Bq/m^3, mitigation measures must be implemented
- If repeat measurement (within 24 months after mitigation measures) is still > 300 Bq/m^3:
  - ✓ Register affected workplaces with competent authority
  - ✓ Carry out dose assessment of the affected workplaces
- Depending on dose estimate additional protection measures must be taken
  - ✓ < 6 mSv/a: optimization in line with general H&S measures
  - ✓ > 6 mSv/a: additional specific radiation protection measures
- Occupational dose limit of 20 mSv/a applies



Examples

- Characterization of Materials
- Dose rates





Paras 3.159–3.181
and Appendix I

Fertilizers production

$$Ca_{10}(PO_4)_6F_2 + 10H_2SO_4 + 20H_2O \rightarrow 10CaSO_4 \cdot 2H_2O + 6H_3PO_4 + 2HF$$

Phosphate ore *phosphogypsum*

^{238}U
^{234}U
^{226}Ra
^{232}Th
^{210}Po
^{210}Pb

^{226}Ra
^{210}Po > 80%
^{210}Pb

^{238}U 86%
^{234}U
^{232}Th 70 %

Fertilizers production

Phosphate Ore			
	Origin	^{238}U Bq/Kg	^{226}Ra Bq/Kg
2013	Syria	926 ± 95	908 ± 82
	Turkey	648 ± 80	590 ± 53
2011	Senegal	1220 ± 90	1345 ± 75
	Algeria	470 ± 30	495 ± 20
2010	Syria	855 ± 160	836 ± 140
2004	Syria	520 ± 77	590 ± 40
	Syria	554 ± 79	580 ± 36
	Morocco	1084 ± 143	1120 ± 150
2003	Morocco	811 ± 90	750 ± 50

Phosphogypsum			
	Sampling point	^{238}U Bq/Kg	^{226}Ra Bq/Kg
2013	basin No 5	17 ± 7	440 ± 21
2010	basin No 1	50 ± 15	420 ± 30
	basin No 4	60 ± 20	375 ± 50
	basin No 5	110 ± 40	585 ± 90
2009	Phosphoric acid Filter	30 ± 5	695 ±50
2005	basin No 2,3	46 ± 9	550 ± 30
	basin No 4	58 ± 8	580 ± 70

Sampling

Fertilizers production

Phosporic acid production industry – In situ measurements

Area Description	Location	Dose rate (nSv/h)
Internal Area	Basement	80-200
Tubes	Basement	180-300
Non metallic tubes	Basement	2200-5000
Cylindrical box	Basement	1.200
Furnace	Basement	120
Whole area	Entresol	< 500
Underneath the filter	Entresol	2800-13000

Fertilizers production

Characterization of materials

Location	Activity concentration (Bq/kg)				
	$^{226}Ra\_max$	^{238}U	^{228}Ra	^{232}Th	^{40}K
Deposition in pipeline	193000	765	1420	1255	260
Dust	487	314	24	21	296

Coal Thermal power station

	Dose Rate(nSv/h)
Coal Mining	100-120

	Activity Concentration (Bq/kg)				
	^{226}Ra_max	^{238}U	^{228}Ra	^{232}Th	^{40}K
Coal / Lignite	319 - 352	181 - 190	15 -18	13 -16	165 - 187

UNSCEAR (2008)
Typical activity concentration values:
^{238}U και ^{232}Th-232: 5 - 300 Bq/kg

Coal Thermal power station

Location	Dose Rate(nSv/h)
Uncovered deposition of ashes	max 360
Covered deposition of ashes	160

	Activity Concentration (Bq/kg)				
	^{226}Ra_max	^{238}U	^{228}Ra	^{232}Th	^{40}K
Flying Ash	528 - 1210	322 -623	24 - 55	24 - 52	250 - 533

UNSCEAR (2008) – Typical values:

^{238}U: 25-3400 Bq/kg ,
^{232}Th: 20-100 Bq/kg,
^{226}Ra: 18-2000 Bq/kg,
^{40}K: 20-1500 Bq/kg

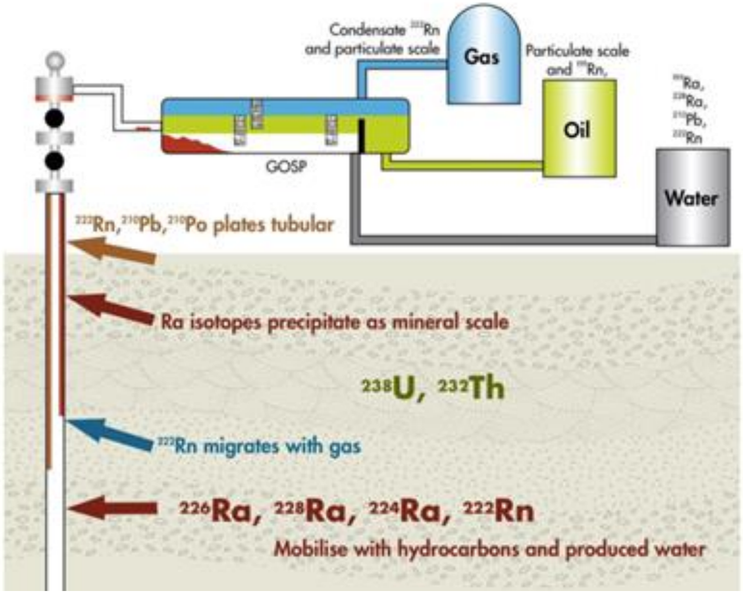
Coal Thermal power station

Location	Dose rate (nSv/h)
Control Room	80
Boiler	100-160
System of filters - old	100-150 In few regions: 150-250 In tubes: Max. 400
System of filters - new	80-100 Max 250 in few dusty areas
Ash Mixing and Storage	160 - 220

Oil industry

	Dose rate (nSv/h)
Byproducts of oil drillings	120-420
Residue tanks	200-4500

	Activity concentration (Bq/kg)		
	^{226}Ra_max	^{232}Th	^{40}K
Waste	73- 206	31-37	219-235
Cleaning Residues	235 - 3140	90-2780	45 - 450



Aluminum production

Aluminum of Greece - premises

	Activity Concentration (Bq/kg)				
	^{226}Ra_max	^{238}U	^{228}Ra	^{232}Th	^{40}K
Greek Bauxite	157	130	193	191	24
Tropical Bauxite	76	58	117	115	<5
Bauxite residues	318	199	397	387	20

Metal recycling industries

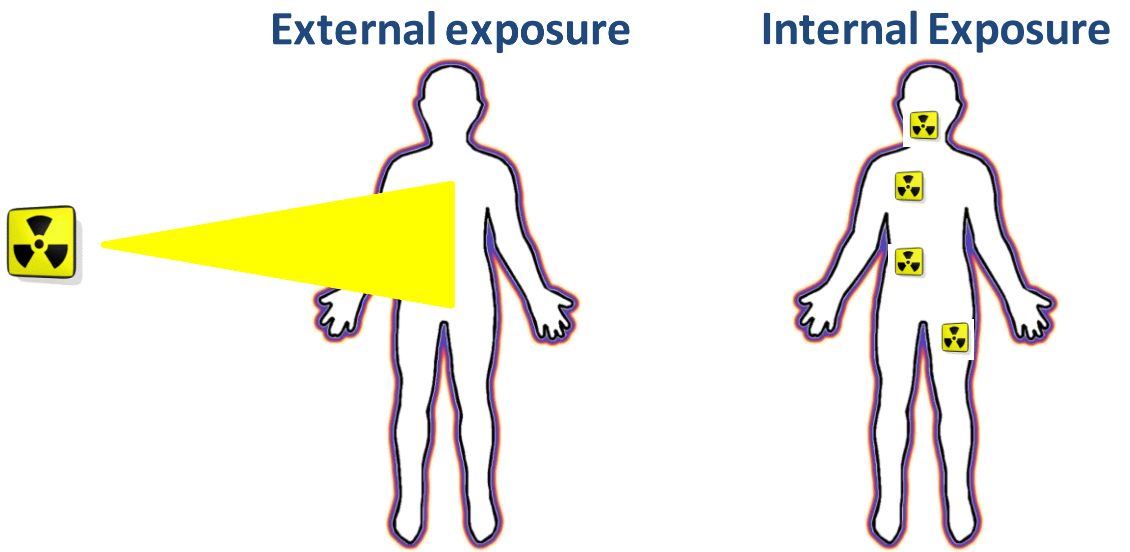
	Activity Concentration (Bq/kg)		
	^{226}Ra_max	^{232}Th	^{40}K
Copper Slag	75-130	30-80	25-75
Steel Slag	< 30	<30	380-580

Issues to be taken into account

- Sampling strategy
- Who is performing the measurements (criteria / recognition procedure)
- Role of the QE, RPO

Exposure pathways

- **External exposure** to gamma radiation emitted from process material
  - Dose rates are generally highest near process tanks, piping, filters and large stockpiles of material
- **Internal exposure** via the inhalation of radionuclides in dust
  - ingestion is unlikely to require consideration under normal operational circumstances
- **Internal exposure** via the inhalation of radon



Dose assessment: External Exposure to gamma radiation

Effective dose $\boldsymbol{E = H^{*}(10) \cdot k \cdot t_{exp}}$

- $H^{*}(10)$ is the ambient gamma dose rate
- $k = 0.6$ is the conversion factor from H*(10) to effective dose
- t_{exp} is the exposure time, often assumed to be 2000 hours per year as default
  - ✓ If more specific information is available, it should be used

- Dose rate H*(10) can be measured (preferred) or roughly estimated using
  - ✓ Geometry parameters
  - ✓ Activity concentration
- Are there simple estimates (rules of thumb)for $H^{*}(10)$?

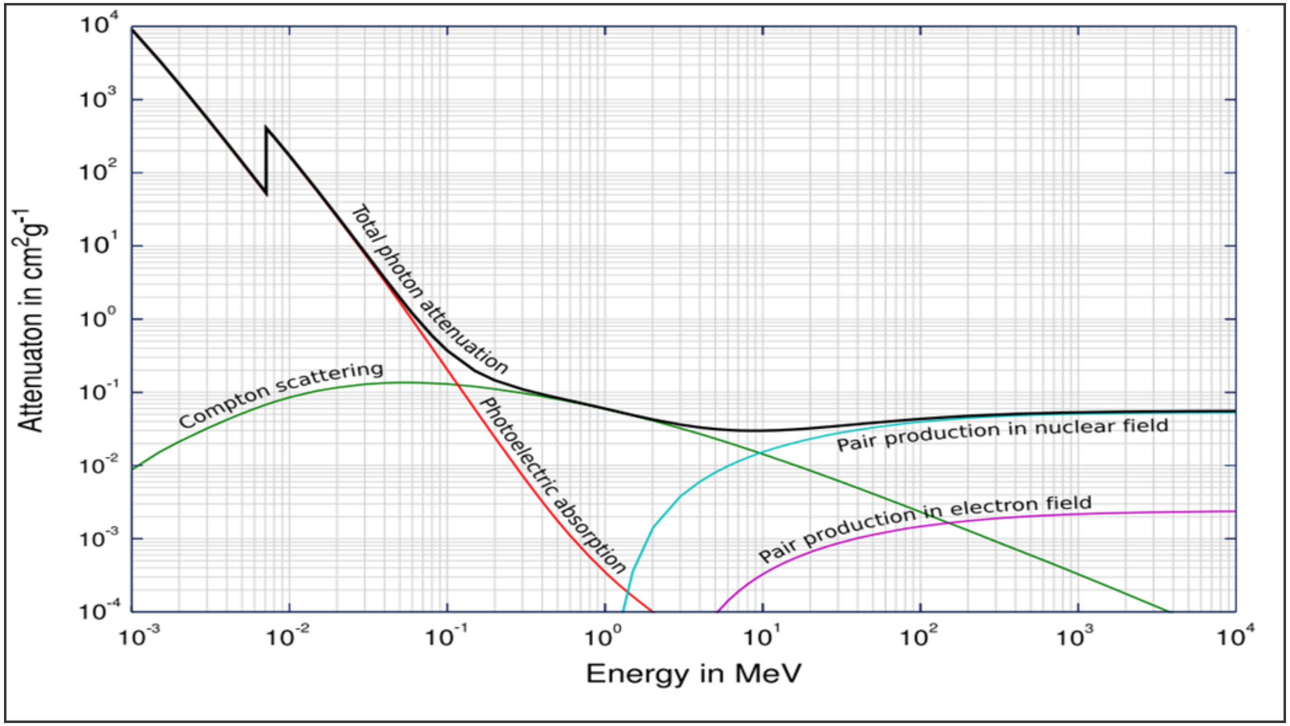
External exposure to gamma radiation

- Assume material of homogeneous activity concentration, infinite thickness
  - ✓ So-called 2π geometry
- The gamma dose rate at the surface of the material is approximately
  - ✓ 0.52 μSv/h per Bq/g Ra-226
  - ✓ 0.7 μSv/h per Bq/g Th-232 (Ra-228)
- Shielding factors may need to be applied
  - ✓ Equipment, truck frame (drivers, operators)
  - ✓ Snow cover (when measuring)

BfS - **Calculation Guide for the Determination of Radiation Exposure due to Environmental Radioactivity Resulting from Mining**

Shielding of gamma radiation

$$I = I_0 \cdot e^{-\mu\left[\frac{cm^2}{g}\right] \cdot \rho\left[\frac{g}{cm^3}\right] \cdot d[cm]}$$

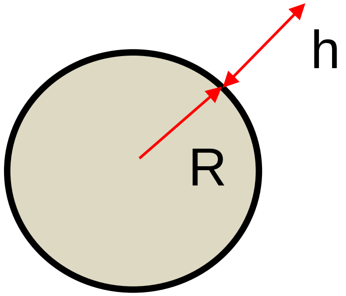


$$H = B \cdot H_0 \cdot e^{-\mu\left[\frac{cm^2}{g}\right] \cdot \rho\left[\frac{g}{cm^3}\right] \cdot d[cm]}$$

Build up factor: energy and material dependent

External exposure by waste drums

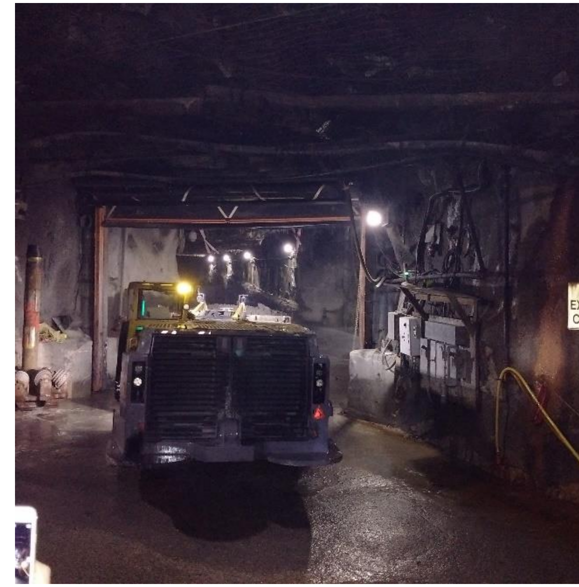
- A drum may be approximated by a sphere or cylinder
- Assume a sphere filled with homogeneous material of activity concentration A (Bq/g).
- The gamma dose rate depends on the distance from the drum's surface approximately as follows:

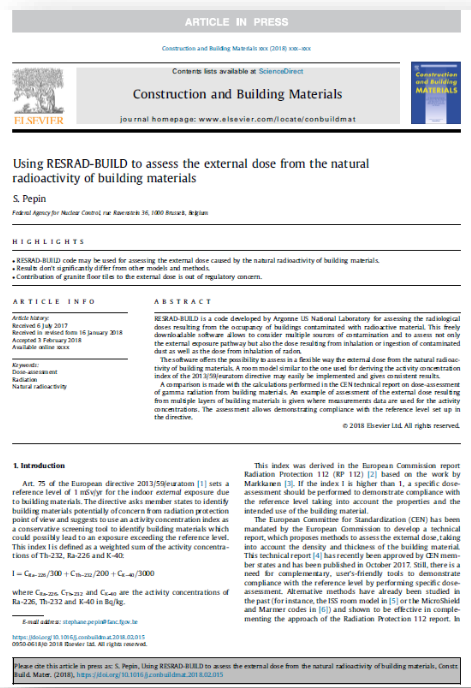


$$H\left[\frac{mSV}{h}\right] = A\left[\frac{Bq\ ^{226}Ra}{g}\right] \cdot 0.052 \cdot \left(1 - \frac{h(2R+h)}{2R(h+R)}\, ln\left(\frac{2R+h}{h}\right)\right)$$

Gamma dose rate in confined geometries

- Example: Confined workplaces in underground mines
- Room dimensions 3 m x 4 m x 2.5 m
- Room model (initially developed for building materials)
  - ✓ RESRAD-BUILD: 3.9 μSv/h per Bq/g Ra-226
  - ✓ CEN TC 17113: 4.4 μSv/h per Bq/g Ra-226
- Compare this with 0.52 μSv/h per Bq/g of the 2π geometry





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Using RESRAD-BUILD to assess the external dose from the natural radioactivity of building materials

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HIGHLIGHTS

- RESRAD-BUILD code may be used for assessing the external dose caused by the natural radioactivity of building materials.
- Results don't significantly differ from other models and methods.
- Contribution of granite floor tiles to the external dose is out of regulatory concern.

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ABSTRACT

RESRAD-BUILD is a code developed by Argonne US National Laboratory for assessing the radiological doses resulting from the occupancy of buildings contaminated with radioactive material. This freely downloadable software allows to consider multiple sources of contamination and to assess not only the external exposure pathway but also the dose resulting from inhalation or ingestion of contaminated dust as well as the dose from inhalation of radon.

The software offers the possibility to assess in a flexible way the external dose from the natural radioactivity of building materials. A room model similar to the one used for deriving the activity concentration index of the 2013/59/euratom directive may easily be implemented and gives consistent results.

A comparison is made with the calculations performed in the CEN technical report on dose-assessment of gamma radiation from building materials. An example of assessment of the external dose resulting from multiple layers of building materials is given where measurements data are used for the activity concentrations. The assessment allows demonstrating compliance with the reference level set up in the directive.

1. Introduction

Art. 75 of the European directive 2013/59/euratom [1] sets a reference level of 1 mSv/yr for the indoor *external* exposure due to building materials. The directive asks member states to identify building materials potentially of concern from radiation protection point of view and suggests to use an activity concentration index as a conservative screening tool to identify building materials which could possibly lead to an exposure exceeding the reference level. This index I is defined as a weighted sum of the activity concentrations of Th-232, Ra-226 and K-40:

$$I = C_{Ra-226}/300 + C_{Th-232}/200 + C_{K-40}/3000$$

where C_{Ra-226}, C_{Th-232} and C_{K-40} are the activity concentrations of Ra-226, Th-232 and K-40 in Bq/kg.

This index was derived in the European Commission report Radiation Protection 112 (RP 112) [2] based on the work by Markkanen [3]. If the index I is higher than 1, a specific dose-assessment should be performed to demonstrate compliance with the reference level taking into account the properties and the intended use of the building material.

The European Committee for Standardization (CEN) has been mandated by the European Commission to develop a technical report, which proposes methods to assess the external dose, taking into account the density and thickness of the building material. This technical report [4] has recently been approved by CEN member states and has been published in October 2017. Still, there is a need for complementary, user's-friendly tools to demonstrate compliance with the reference level by performing specific dose-assessment. Alternative methods have already been studied in the past (for instance, the ISS room model in [5] or the MicroShield and Marmer codes in [6]) and shown to be effective in complementing the approach of the Radiation Protection 112 report. In

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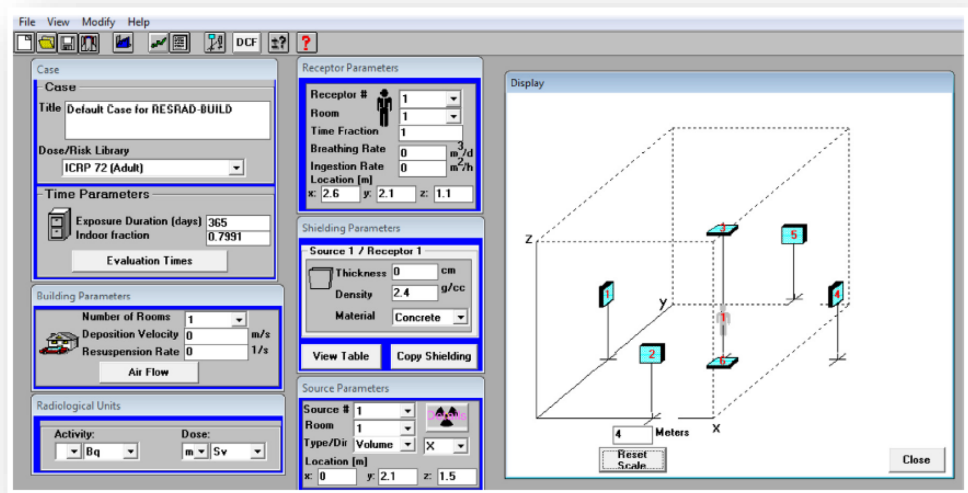


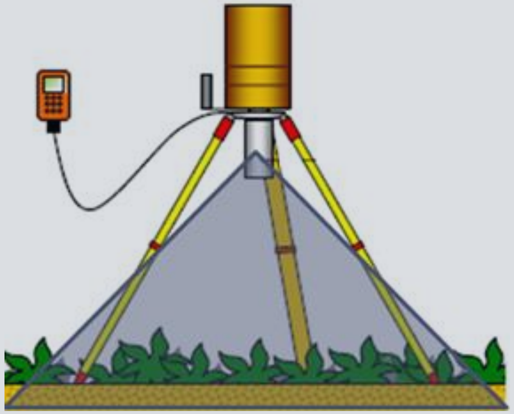
In situ Measurements

$$C = \frac{\dot{N}_f}{A} = \frac{\dot{N}_0}{\varphi} \cdot \frac{\dot{N}_f}{\dot{N}_0} \cdot \frac{\varphi}{A}$$

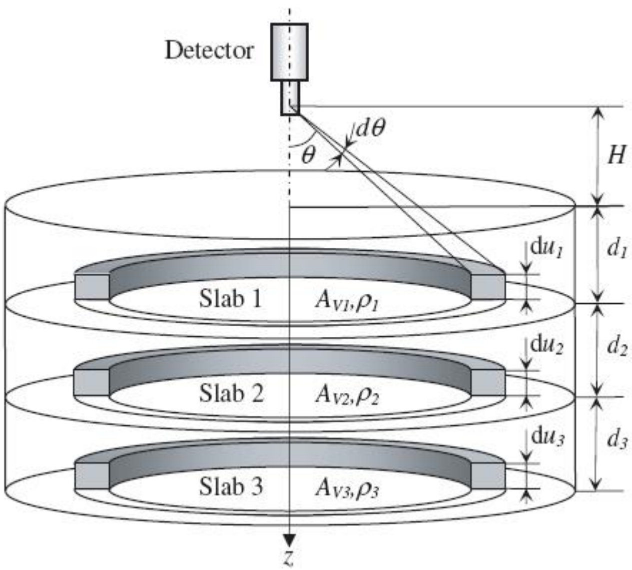
$\frac{\dot{N}_0}{\varphi}$ **the full-energy peak count rate, per unit fluence** rate of a parallel photon beam–with energy E –perpendicular to the detector front window.

$\frac{\dot{N}_f}{\dot{N}_0}$ **the angular correction function for the detector** response at energy E, to account for the facts that: (a) there is not a parallel beam of photons (b) the detector response depends on the photon angle.

$\frac{\varphi}{A}$ **the fluence rate**, of energy E photons emitted from a specific radionuclide, that reach the detector unscattered, **per unit activity** of the radionuclide.



Calibration:
- Semi-empirical
- Monte Carlo simulation



Exposure to dust (inhalation pathway)

$$E\left(\frac{Sv}{h}\right) = T \cdot \sum_{i}^{n} A_i \cdot e(g)_i$$

For the i-relevant radionuclides:

- A_i: the activity intake rate (Bq/h)
- $e(g)_i$: the nuclide specific dose convention factor (Sv/Bq)
- T: the exposure time (h)

Radionuclide[a]	Physical half-life	Inhalation			
		Type	f_1	$e(g)_{1\,\mu m}$	$e(g)_{5\,\mu m}$
Uranium					
		S	0.002	8.7×10^{-6}	6.9×10^{-6}
U-234	2.44×10^{5} a	F	0.020	5.5×10^{-7}	6.4×10^{-7}
		M	0.020	3.1×10^{-6}	2.1×10^{-6}
		S	0.002	8.5×10^{-6}	6.8×10^{-6}
U-235	7.04×10^{8} a	F	0.020	5.1×10^{-7}	6.0×10^{-7}
		M	0.020	2.8×10^{-6}	1.8×10^{-6}
		S	0.002	7.7×10^{-6}	6.1×10^{-6}
U-238	4.47×10^{9} a	F	0.020	4.9×10^{-7}	5.8×10^{-7}
		M	0.020	2.6×10^{-6}	1.6×10^{-6}
		S	0.002	7.3×10^{-6}	5.7×10^{-6}

Exposure to dust (inhalation pathway)

$$\boldsymbol{E}\left(\frac{\boldsymbol{Sv}}{\boldsymbol{h}}\right) = \boldsymbol{T} \cdot \sum_{\boldsymbol{i}}^{\boldsymbol{n}} \boldsymbol{A}_{\boldsymbol{i}} \cdot \boldsymbol{e}(\boldsymbol{g})_{\boldsymbol{i}}$$

For the i-relevant radionuclides:

- $\boldsymbol{A_i}$: the activity intake rate (Bq/h)
- $\boldsymbol{e(g)_i}$: the nuclide specific dose convention factor (Sv/Bq)
- $\boldsymbol{T}$: the exposure time (h)
- The intake rate could be also considered:
  - ✓ [specific activity of the dust] x [dust concentration] x [breath rate]
  - ✓ [activity concentration in the air] x [breath rate]
  - ✓ Different size classes could be also taken into account
- Protective equipment → e.g. a mask might may lead to a factor of 0.5 could be measured

Exposure to radon (inhalation pathway)

$$E = C_{Rn-222} \cdot F \cdot k_{Rn} \cdot T$$

For the i-relevant radionuclides:

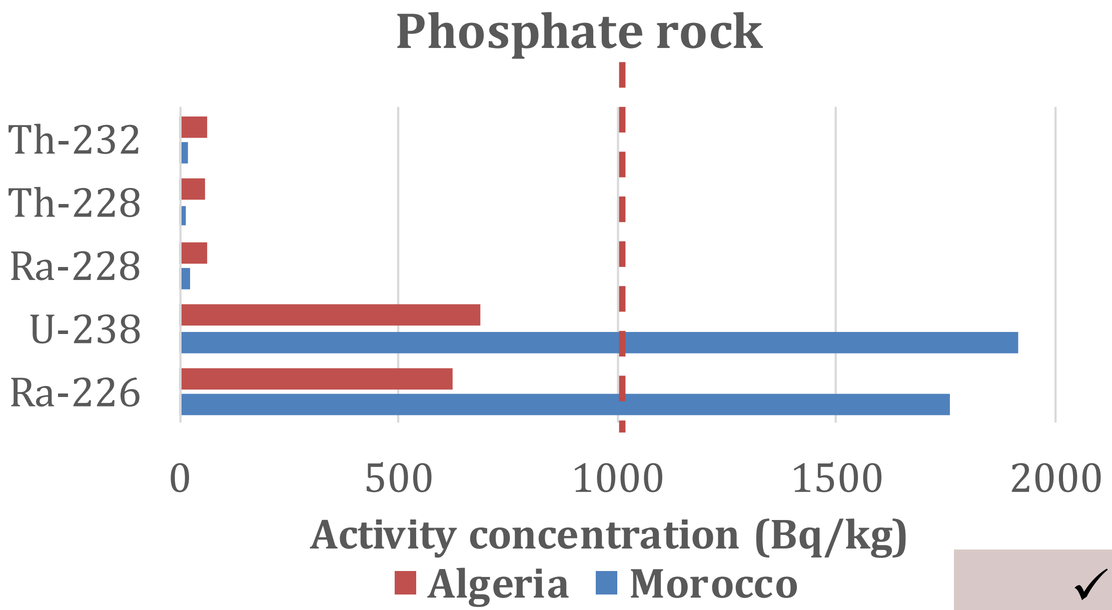
- C_{Rn-222}: the activity concentration of Rn-222
- $k_{Rn} = 7.8 \cdot 10^{-9} \frac{Sv}{h} \; per \; Bq/m^3$
- F is the equilibrium factor between daughters and parent nuclide, often assumed as 0.4, in ventilated working environments might be less (<0.1 – 0.2)

Uncertainties ?

Occupational exposure

CASE STUDY – PHOSPHATE INDUSTRY

Case study – Setting the scene



- ✓ Cannot **be released from regulatory control**
- ✓ **Dose assessment** is required

		Equivalent dose rate (nSv/h)
Phosphate rock storerooms		
✓	Morocco	170-1050
✓	Algeria	30-650
Operation rooms		max 50

Case study –
Assumptions for the Dose Assessments

Exposure scenaria

- **Phosphate rock storerooms**
  - ✓ Normal working conditions
  - ✓ Extreme working conditions
- **Operation rooms** (occupancy factor 1)

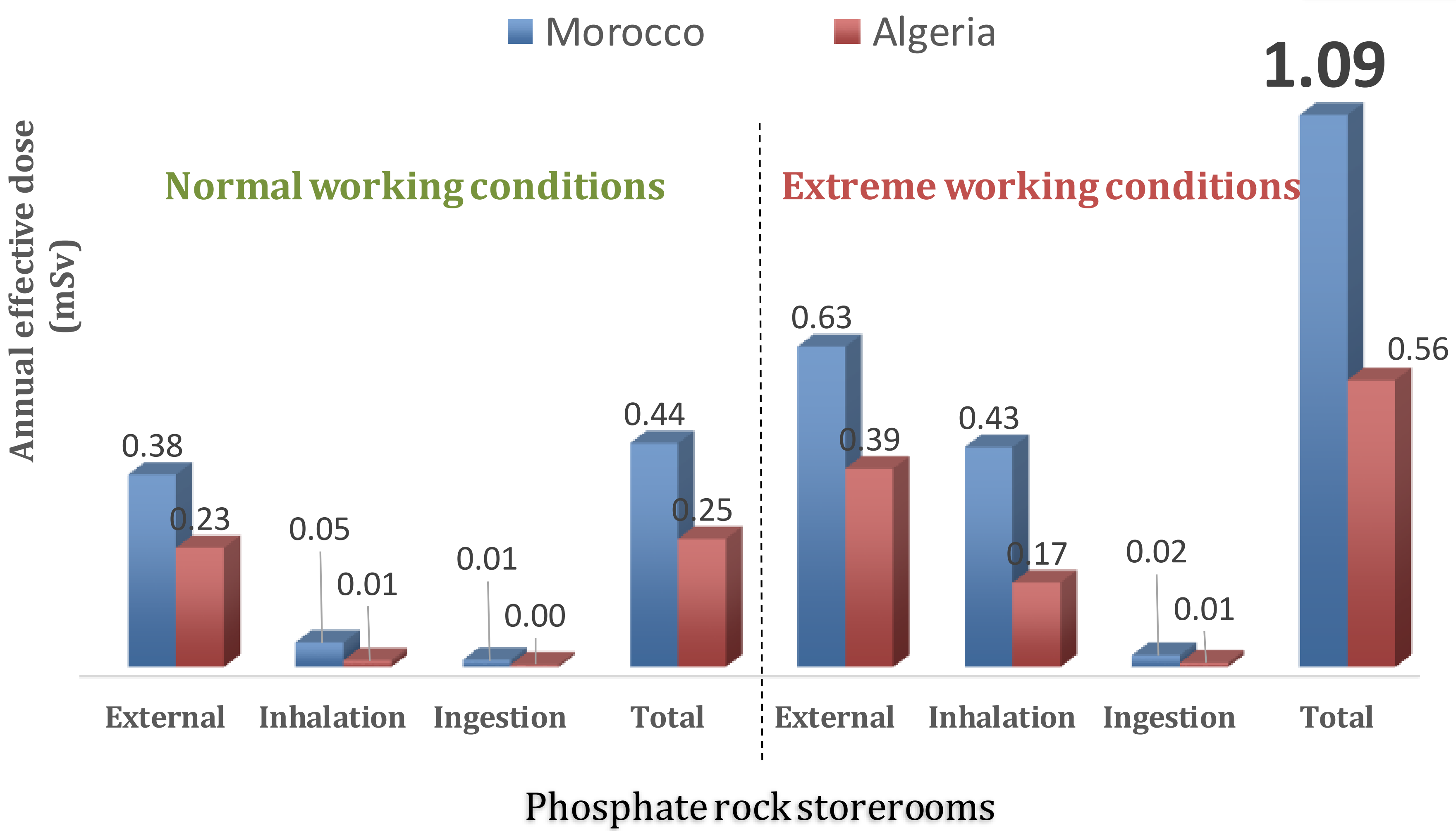
Exposure pathways

- Dust inhalation
- Dust ingestion
- External exposure

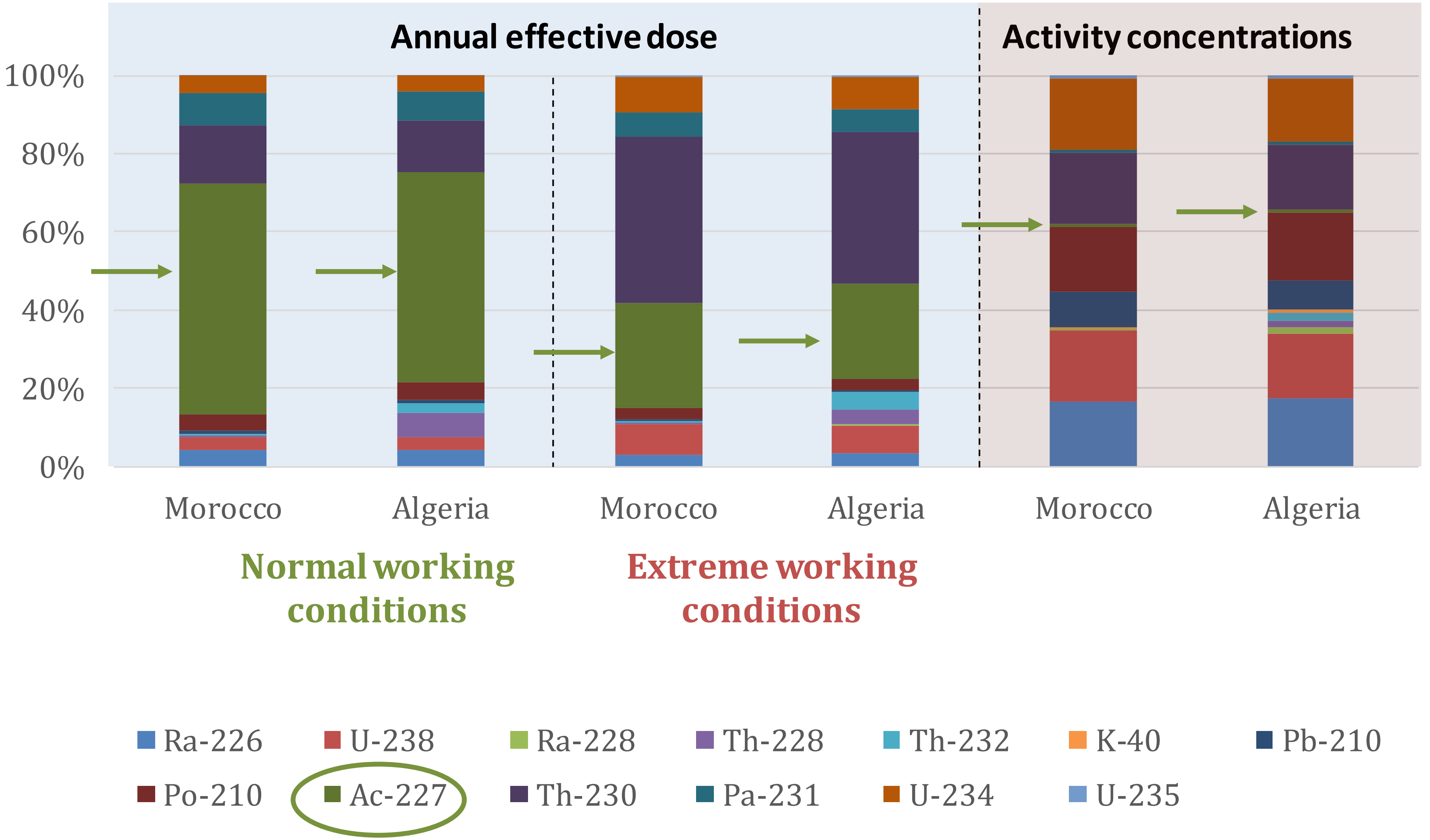
	Normal	Extreme
AMAD (μm)	5	1
Air dust load (mg/m^3)	1	2
Occupancy factor	0.3	0.5
Breathing rate (m^3/h)	1.2	
Ingestion rate (mg/h)	10	
Working hours per year	2000	

Case study – Assessed dose

Operation room:
0.06 mSv/y

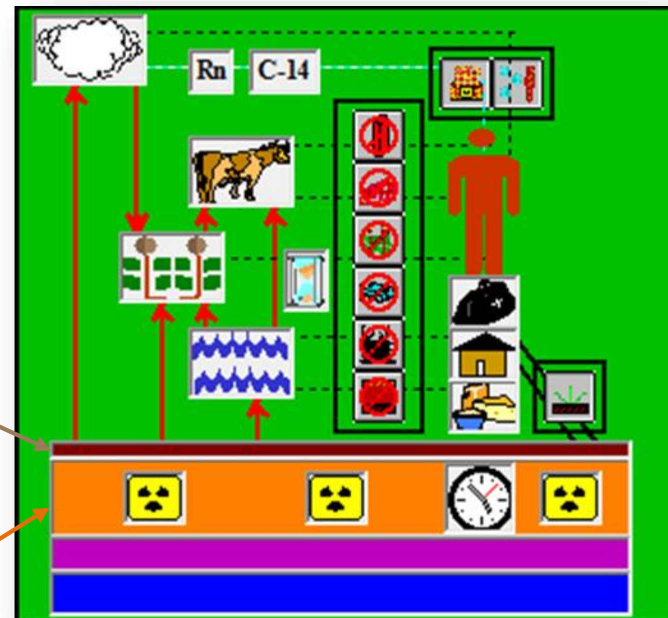


Case study –
Assessed dose - Contribution of radionuclides



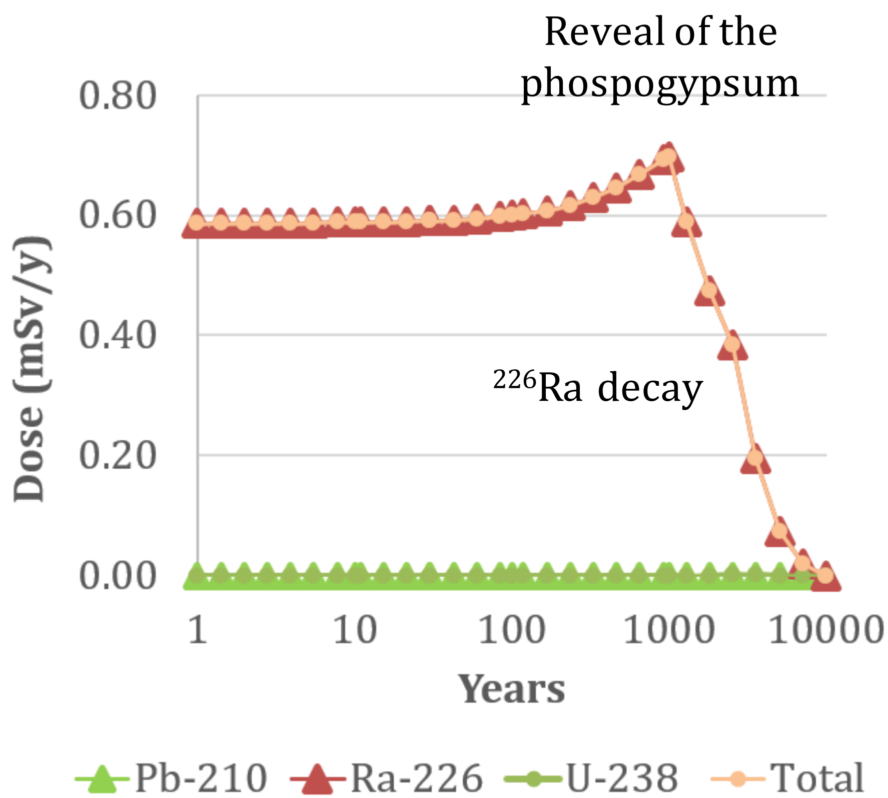
Case study –
RESRAD software

- Radon
- Inhalation
- External exposure



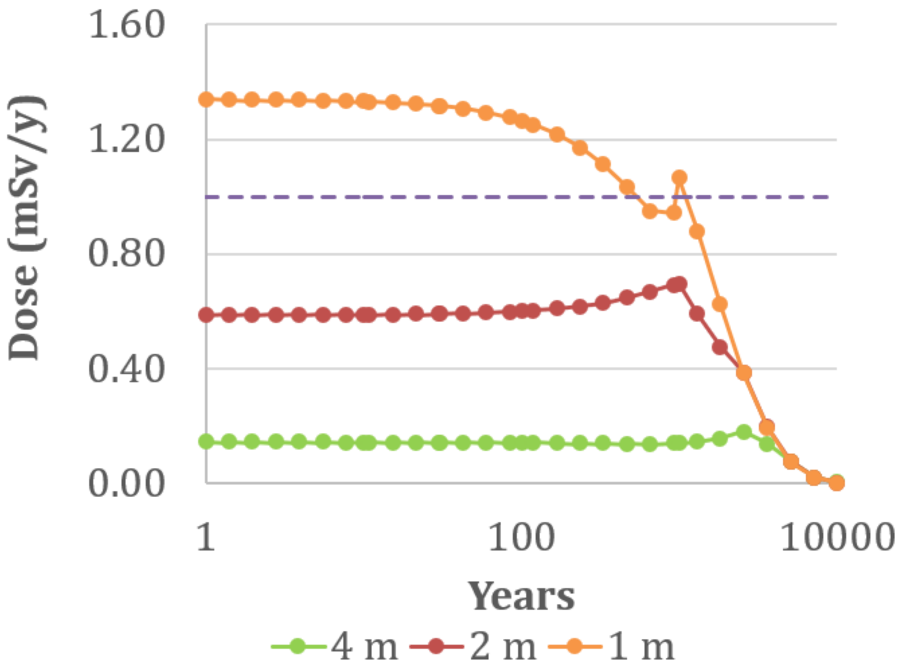
RESRAD on-site

Case study –
RESRAD software - Results

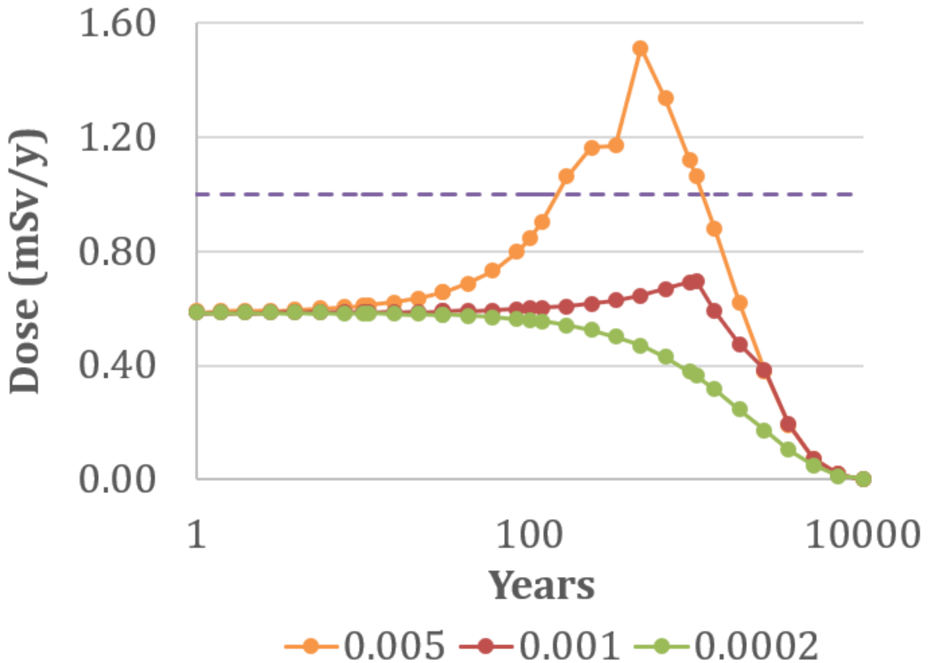


Case study –
RESRAD software - Results

Soil - Cover thickness



Erosion rate - Soil



Conclusions

- Regulatory control of industries involving NORM **is a challenge** and an open issue.

- Characterization of materials and processes and realistic dose assessments are the first step for the both **an efficient and effective regulatory control** as well as the further optimization through the radiation protection programme.

- Most relevant exposure pathways
  - ✓ Direct external exposure
  - ✓ Inhalation to dust
  - ✓ Exposure to radon

Conclusions

- Simple Bq/g to mSv/y relationships **are useful generic screening tools**, but may not be always sufficient.
- Understand the technological process and hence the typical nuclide vector of materials involved .
- Adequate sampling strategy.
- Scientific data when used appropriately can lead to realistic assessments.
- Software can lead to realistic assessments if realistic parameters have been selected.

Thank you very much for your attention!

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