Realistic dose assessment in industrial activities involving NORM

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Learning objectives

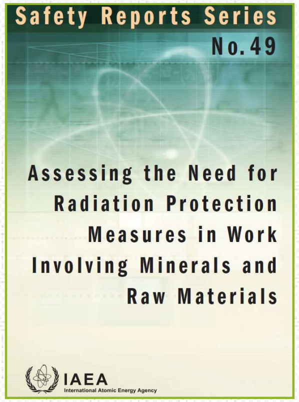
- Become familiar with a modern regulatory approach to control occupational exposure,
  - Example of the new legal and regulatory radiation protection framework of Germany
- Develop an understanding of the relationship between the technological processes, materials and exposure situations typical for each sector, and most relevant exposure pathways
- Understand the importance of realistic scenarios and plausible assumptions for occupational dose estimates

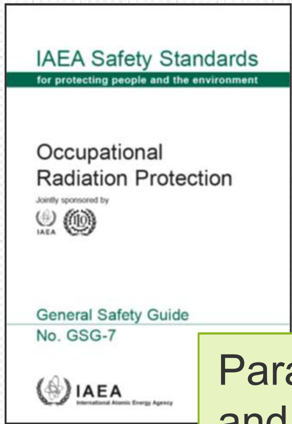
Outline of the Webinar

- Regulatory framework and standards
  - IAEA GSG-7 (2018) and SR-49 (2006)
  - Example: Germany, new RP law (2017) and new RP Ordinance (2018)
  - "White Lists" of potentially relevant NORM workplaces: example from Germany
  - Requirements related to occupational exposure under the new regulatory framework in Germany
  - National dose register and NORM workplaces, recent studies on potentially relevant workplaces
- Guidance documents for dose assessments
- Important exposure pathways: direct radiation, inhalation of dust, radon
  - Dose models: scenarios, assumptions and parameters
  - Rules of thumb and simple models
  - Selected examples

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





Paras 3.159–3.181
and Appendix I

Regulatory framework: Germany

- New Radiation Protection Law (2017)
  - Transposes EU BSS (Directive 2013/59/Euratom) into national law
  - Covers practices in NORM industry sectors (planned exposure)
  - "White List" of NORM industrial sectors with potentially relevant workplaces
  - Qualified experts (notified by authority) are now required to assess occupational exposure
  - Includes radon at workplaces (see next slides)
  - Radon must be measured by a notified body
- New Radiation Protection Ordinance (2018) specifies requirements on occupational radiation protection, including in NORM sectors

White List of practices (Appendix 3 to the Law, simplified)

- Grinding and use of Th welding rods
- Work involving Th gas mantles, optical components, alloys
- Use of natural U and Th for analytical work
- Mining, use and processing of pyrochloric ores
- Use and processing of slags from smelters of copper slate
- Processing of Nb/Ta ores, Zr refractories
- Handling of sludge and scale from production and processing of oil, gas, and geothermal energy
- Maintenance of clinker furnace coatings in cement production and boilers in power plants
- Remediation of contaminated land and storage of NORM residues

Similar “White Lists“ exist in EU BSS 2013/59/EURATOM and IAEA GSG-7

Requirements on dose assessment of NORM workplaces

- If workplace is on White List (or if competent authority deems it necessary), a dose estimate has to be carried out prior to commencing the work
- Dose estimate must be carried out by qualified expert
- If effective dose is likely to exceed 1 mSv/a, the authority must be notified, including
  - 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
- Authority reviews the submitted documents and may suspend/prohibit the activity if deemed necessary
- Occupation dose limit of 20 mSv/a applies

Radon at workplaces: existing exposure situation

- Rn-222 at indoor workplaces is regulated under the new Law
- Reference value of 300 Bq/m³
  - One third of IAEA GSR Part 3 (1000 Bq/m³, see also Para 5.60 of GSG-9)
- Requirement to measure Rn concentration, if…
  - Activity appears under Appendix 8 (“Radon White List“)
    - Underground mines, caves and museum mines
    - Radon spas
    - Water supply and treatment facilities
  - Workplace is on ground floor or basement in a „radon-prone area“
- 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/m³, mitigation measures must be implemented
- If repeat measurement (within 24 months after mitigation measures) is still > 300 Bq/m³:
  - Register affected workplaces with competent authority
  - Carry out <u>dose assessment</u> 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

Occupationally exposed workers in the German dose register

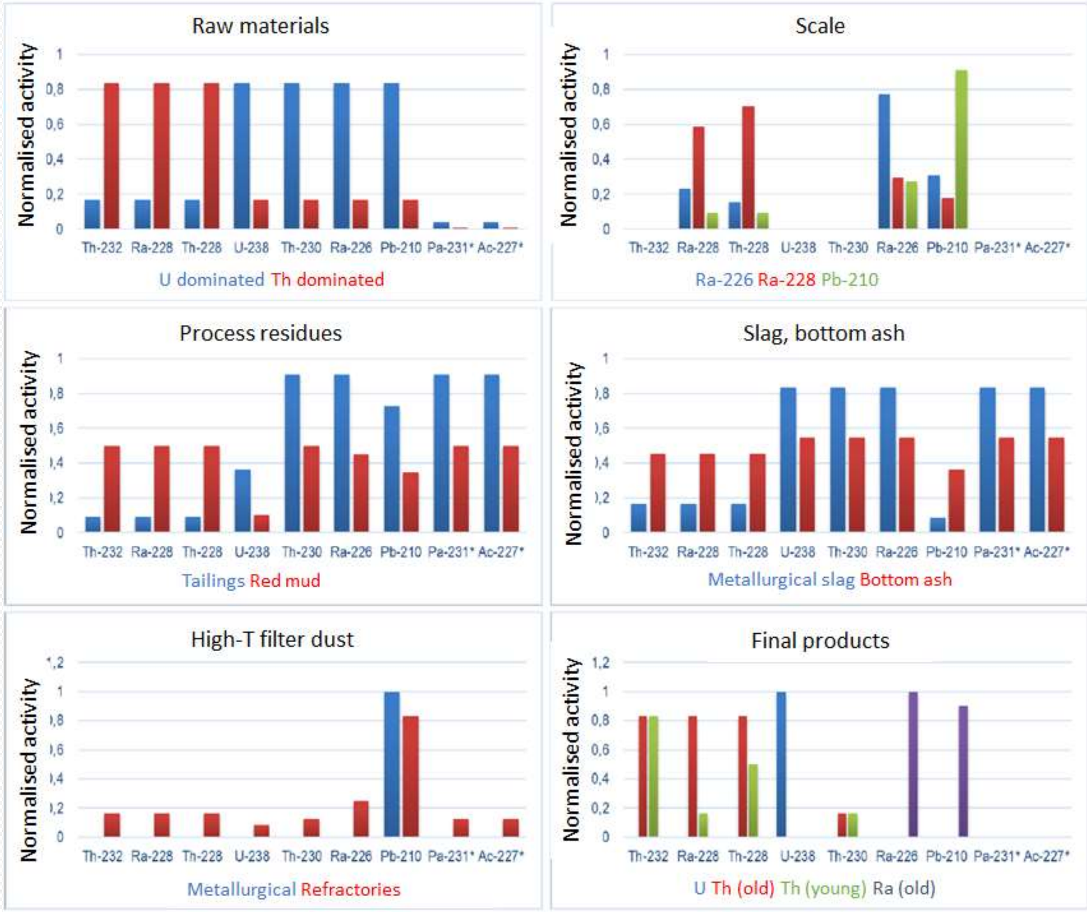
- Approx. 200 people at NORM workplaces
  - Excluding miners at former uranium production sites of Wismut
- Underground mines (including tourist mines), caves, radon spas
- Average effective annual dose of registered persons is approxiately 4-5 mSv
- Source: Federal Office for Radiation Protection https://www.bfs.de/DE/themen/ion/strahlenschutz/beruf/strahlenschutzregister/strahlenschutzregister-auswertungen.html
- Under the new Law, more workers will need to be registered

Most recent study (2017) on occupational exposure in Germany (NCC, contracted by the Office for Radiation Protection)

- Questions:
  - Number of employees/workplaces for which a dose estimate is required under the new Radiation Protection Law
  - Number of employees/workplaces for which an occupational dose of >1mSv/a is expected
  - In addition to already regulated and registered sectors
- Industries considered
  - Processing of Niobium-Tantalum ores/concentrates
  - Operation and maintenance of geothermal installations
  - Production and handling of thoriated tungsten alloys
  - Maintenance of klinker ovens
  - Processing of zirconium materials (refractories)
  - Handling of residues of oil/gas production and geothermal installations
  - Remediation of contaminated sites and storage of residues

Methodology

- Process-based categorisation of NORM: 6 nuclide „signatures“ (IAF and NCC in 2005)
- This approach allows to
  - Consider <u>all</u> relevant nuclides (incl. Th-230, Po-210 with high DCF)
  - Easily scale-up unit dose with activity concentration (e.g., in dust)
  - Screen entire groups of NORM industries with the same type of production process
- Literature data, workplace measurements (γ, dust), lab analyses of selected materials
- Survey of occupancy time and an estimate of employees that may be affected



Findings of the NCC study

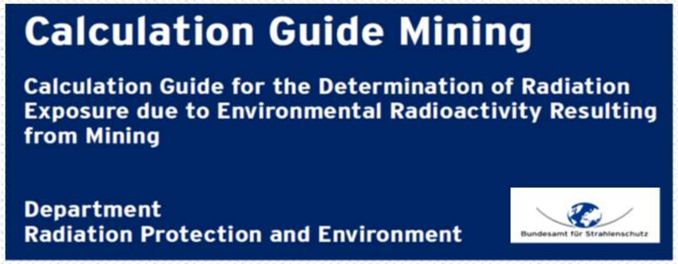
Industry sector	Estimated number of additional workplaces warranting detailed dose assessments, Germany	Estimated number of additional workplaces with >1 mSv/a (notification of authorities), Germany
Processing of Niobium-Tantalum ores/concentrates Operation and maintenance of geothermal installations Processing of zirconium materials (refractories) Remediation of contaminated sites and storage of residues Maintenance of furnaces	30-100 per sector	Zirconium materials, production of thoriated alloys: 10-30 Others: 3-10 per sector
Handling of thoriated tungsten alloys (assembly of parts of alloys)	10-30	3-10
Handling of residues of oil/gas production and geothermal installations	100-300	10-30
Total (rounded)	**250-800**	**45-130**

Existing studies with dose estimates for NORM workplaces (Germany, Austria)

- Germany (2006): various industries
- Metal Processing Industry (2008): thoriated welding rods
- EAN_{NORM} (now ENA) industry fact sheets, e.g., Zirconium industry (2010)
- Austria (2011): various industries
- Bavaria (2004, 2015): various industries
- Oil/gas Industry Training Center (2018): cleaning of radioactive scrap and transport/disposal of scale
- All studies arrive at ranges of doses and are based on typical material parameters and exposure scenarios
- It is common to derive a relationship of the type “dose [mSv/a] per activity concentration of the material involved [Bq/g]“, based on generic scenarios
- While this approach is useful as a screening tool, a detailed understanding of the exposure situation of a specific workplace is necessary

Dose calculation guideline for mining (Germany)

- Issued by the Federal Office for Radiation Protection (1999, updated 2011)
- Initially intended for dose assessment of uranium /radioactive minerals mining & processing facilities
- It is now considered a valuable resource for dose calculations in other sectors, too
  - Relevant parameters (transfer factors)
  - Assumptions and standard scenarios
  - Dose conversion factors of all natural radionuclides
- External exposure, ingestion, inhalation of dust inhalation of radon/progeny
- Also available in English (deep link, google “BfS Dose Calculation Guide Mining“



Dose assessment: External exposure to gamma radiation

- Effective dose $E = H^*(10) \cdot k \cdot t_{exp}$
- $H^*(10)$ 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 on a flat surface

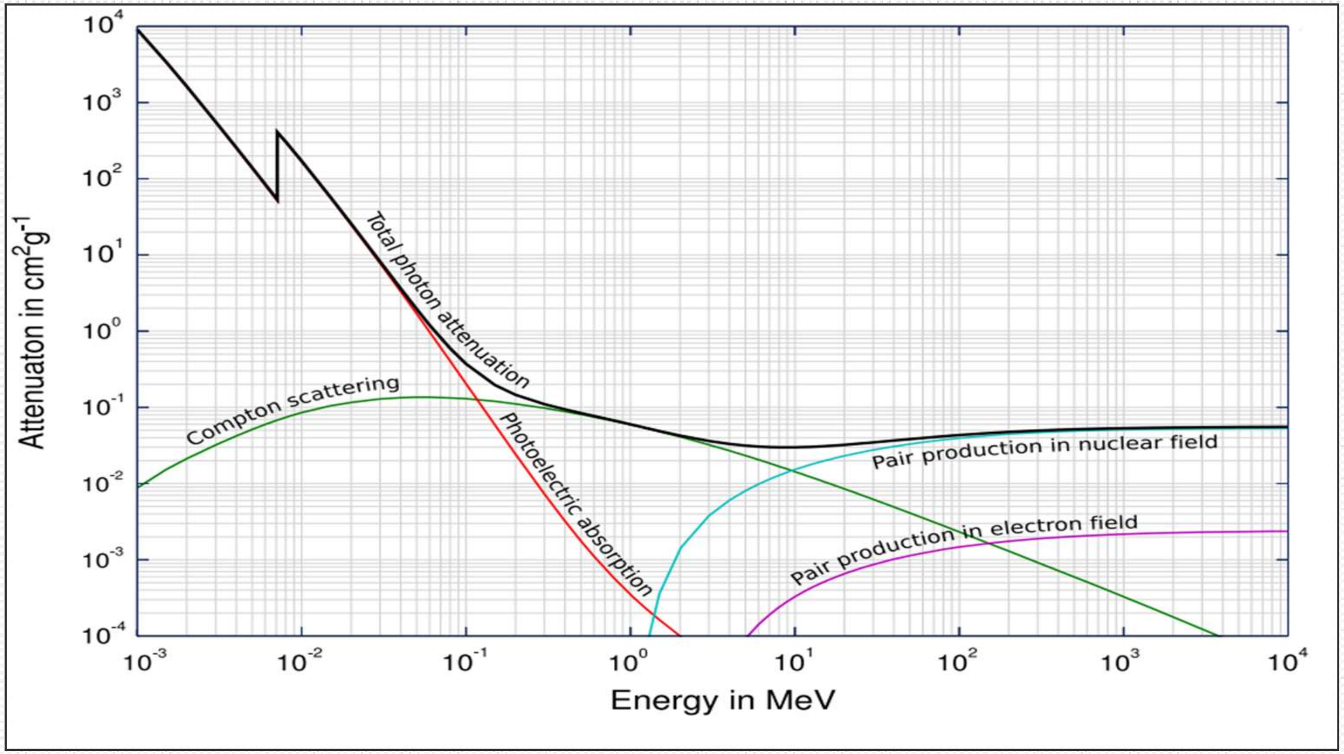
- Assume material of homogeneous activity concentration, infinite thickness
  - So-called 2π geometry
- The gamma dose rate at the surface of the material is approximately
  - 0.52 µSv/h per Bq/g Ra-226
  - 0.7 µSv/h per Bq/g Th-232 (Ra-228)
- Shielding factors may need to be applied
  - Equipment, truck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

Shielding of gamma radiation

- $H = H_0 \cdot e^{-A\left[\frac{cm^2}{g}\right] \rho\left[\frac{g}{cm^3}\right] d[cm]}$
- Energy dependent, see diagram
- Examples: 2π geometry, E = 1 MeV
  - Bulldozer driver on a 2 cm thick steel frame
    - ρ = 7.8 g/cm³
    - H/H_0= 0.45
  - Snow cover, 20 cm
    - ρ = 0.3 g/cm³
    - H/H_0= 0.75

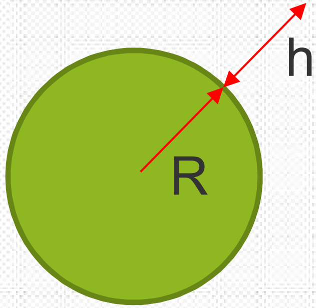
Photo: Wismut GmbH

Energy-dependent photon shielding coefficient

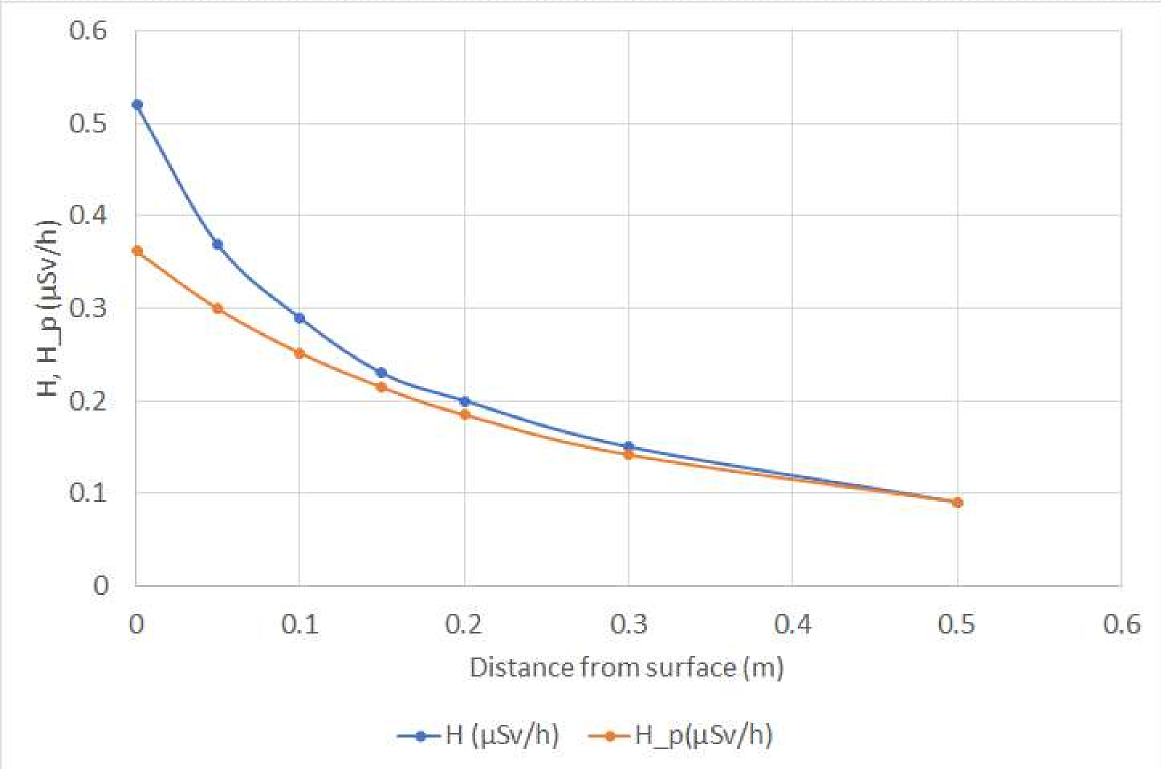


External exposure by waste drums

- 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 H depends on the distance from the drum‘s surface approximately as follows:
- $H\left[\frac{\mu Sv}{h}\right] = a\left[\frac{Bq\ Ra{-}226}{g}\right] \cdot 0.052 \cdot \left(1 - \frac{h(2R+h)}{2R(h+R)} \ln\left(\frac{2R+h}{h}\right)\right)$



Gamma dose rate of a homogeneous sphere



Example:
A = 10 Bq/g
R (diameter of drum) = 0.5 m

As expected, at a distance h >> R, the dose rate decreases ~ $1/h^2$

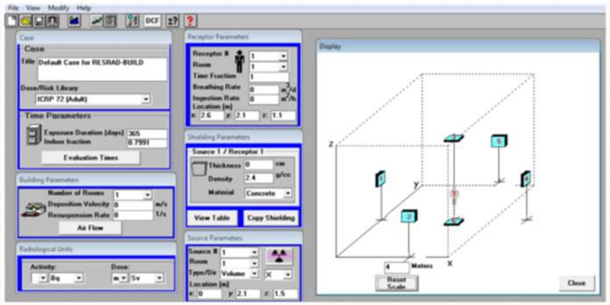
...like the dose rate H_p of a point source of the same total activity

For drums in a row, the decrease of the dose rate is less pronounced.

As a rule of thumb, the dose rate decreases by a factor of 2-3 for each meter of distance.

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



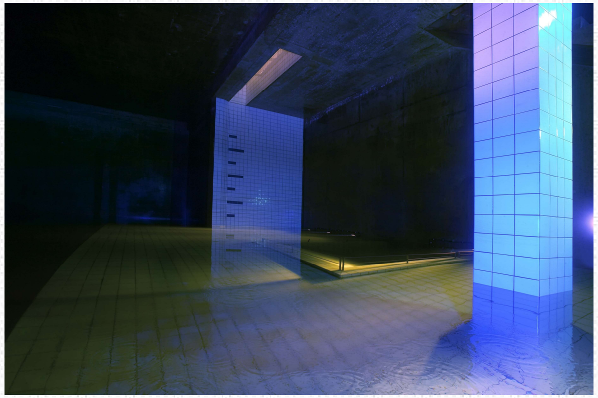
From S. Pepin: Using RESRAD-BUILD to assess the external dose from the natural radioactivity of building materials, Construction and Building Materials 168 (2018) 1003–1007

Exposure to radon (Rn-222)

- Dose can be calculated using Rn concentration and equilibrium factor
  - $E = c_{Rn\text{-}222} \cdot F \cdot k_{Rn} \cdot t_{exp}$
  - k_{Rn} = 7.8E-9 Sv/h per Bq/m³
- F is the equilibrium factor between daughters and mother nuclide
  - As a default, it is often assumed to be 0.4
  - Realistically, F <u>may</u> be much less than that, e.g., in ventilated mines (<0.1-0.2)
- Alternatively, the exposure to radon and its progeny can be described using the potential alpha energy concentration (PAEC)
  - $E = c_{pot} \cdot k_{pot} \cdot t_{exp}$
  - k_{pot} = 1.4 Sv/h per J/m³

Examples for Rn exposure of workers

- Water utilities
  - Groundwater wells, water storage tanks etc.
  - Rn concentration may reach several 1,000-10,000 Bq/m³
  - Occupancy is restricted to few hours per week, restricted to the absolutely necessary
  - Assume 5,000 Bq/m³, F=0.4, t_{exp} = 100 h/a, then E = 3 mSv/a
  - Mitigation: ventilation prior to entering the facility is an easy and effective
- Ore mines
  - Equilibrium Rn concentrations (without ventilation) can reach several 10,000-100,000 Bq/m³
  - Selective workplace ventilation can reduce this to several 100 Bq/m³
  - Assume 1,000 Bq/m³, F=0.1, t_{exp} = 2000 h/a, then E = 1.5 mSv/a


T. Tennstedt, BWB Berlin

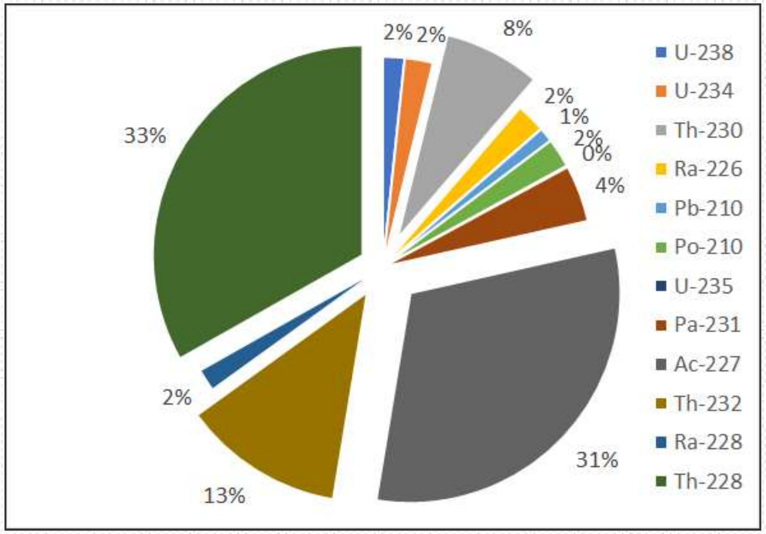
Exposure to dust (inhalation pathway)

- $E[mSv/a] = \sum_i DCF_i\ [mSv/Bq] \cdot \dot{A}_i \cdot t_{exp}$
- For all relevant nuclides i
  - $\dot{A}_i$ is the activity intake rate (Bq/h)
  - DCF_i is the nuclide-specific dose conversion factor (mSv per Bq)
  - t_{exp} is the exposure time (usually occupancy of the workplace)
- The intake rate can be expressed as
  - [Specific activity a_i of the dust] x [dust concentration c] x [breath rate]
  - [Activity concentration in the air] x [breath rate]
- Dust may be subdivided further into different size classes (omitted here for simplicity).

Nuclide	DCF (µSv/Bq)
U-238	1.6
U-234	2.1
Th-230	7.2
Ra-226	2.2
Pb-210	1.1
Po-210	2.2
U-235	1.8
Pa-231	89
Ac-227	630
Th-232	12
Ra-228	1.7
Th-228	32

A simple exercise: relative contributions of nuclides to the total inhalation dose

- Assume dust with full equilibrium of all nuclides in either of the U-238 and Th-232 series
- Assume same specific activity of U-238 and Th-232
- Note that in all NORM, the activity ratio of U-238/U-235 is 21.
- Question: which nuclides have the highest relative contribution to the effective dose resulting from inhalation?
- Answer:
  - In uranium series: Ac-227 and Th-230
  - In thorium series: Th-228



- In practice full equilibrium is rarely the case due to redistribution and accumulation processes

Inhalation of dust: the example of thoriated welding rods

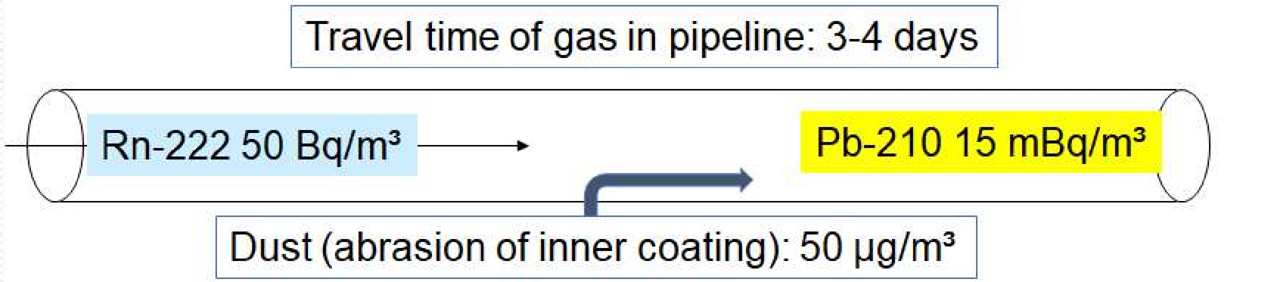
- Some industries have „rules of thumb“. Use them but check for plausibility.
- Example: Employers‘ Liability Insurance of the Wood and Metal Processing Industry (Germany)
  - AC welding using thorium electrodes WT20 (2% ThO2): 4.2 µSv/h from the inhalation of dust.
  - How plausible is this?
- Workplace monitoring data:
  - Dust concentration behind welder‘s face shield: 1.62 mg/m³
  - 70-100% of dust is in alveolar fraction

Thoriated welding rods: plausibility check

- Assume 100% of measured dust is alveoloar and stems from the electrode material
- 1.62 mg/m³ corresponds to 0.11 Bq/m³ Th-232
- Breathing rate of workers: 1.2 m³/h → activity intake is 0.13 Bq/h of Th-232
- Assumption of equilibrium between Th-232 and Ra-228 and Th-228 („old“ material)
- Applying the dose conversion factors leads to a dose rate of 6.3 µSv/h
  - Industry „rule of thumb“ rate is plausible
- For a workplace occupancy of 1000 h/a, the effective dose is 6.3 mSv/a
- This clearly calls for dust protection measures

	DCF (Worker), Sv/Bq
Th-232	1.20E-05
Ra-228	1.70E-06
Th-228	3.20E-05

Dust: transport of natural gas in pipeline networks



Gas transport

- 15 mBq/m³ Pb-210 on 50 µg/m³ of dust → 300 Bq/g Pb-210
- Ingrowth of Po-210 occurs within a few months until equilibrium with Pb-210 is reached
- Maintenance of filters (replacing cartridges) can lead to increased doses
- Assume 1 mg/m³ of dust and an exposure time of 8 hours per shift
- Effective dose per shift due to inhalation of dust is 9 µSv
  - 3 µSv from Pb-210
  - 6 µSv from Po-210

Nuclide	DCF (µSv/Bq)
Pb-210	1.1
Po-210	2.2

- This confirms the general finding of several recent studies that specialised industrial service providers (maintenance, recycling, cleaning) require particular attention because of high occupancy rates

General occupational HSE requirements: constraints on dust concentrations at workplaces

- TRGS 900 (Technical Rules for Hazardous Substances at Workplaces, Germany)
  - Alveolar dust 1.25 mg/m^3 average per shift
  - Inhalable dust 10 mg/m^3
  - Not applicable to toxic or cancerogenic dust: specific risk assessment required
  - Additional protection measures may be required
- These limits also constrain the occupational exposure to radioactive dust
- Assume that the limit for "conventional" inhalable dust (10 mg/m^3) is complied with
- The worker is exposed 2000 h/a to the dust concentration of 10 mg/m^3
- If the activity concentration of all nuclides of the U-238 decay series is 0.8 Bq/g (and that of the U-235 series is 1/21 of the U-238 series), the effective dose due to inhalation is 1 mSv/a

Realistic determination of the (potential) activity intake at a workplace

- Workers are given respiratory protection masks and wear them throughout their working day
- After sufficient exposure time, filters are analysed
- Activity retained on filter reflects the activity intake under normal workplace conditions, if no respiratory protection would be worn
- Take retention factor of filtering face pieces (FFP) into account
  - FFP-1 ≤25% leakage
  - FFP-3 ≤ 5% leakage
- Some blanks must also be analysed to check for the filter background
  - Some glass fiber filters may contain increased Pb-210/Po-210 activities
  - Deposition of Pb-210 during storage of filters prior to use

Some materials/industry sectors, and most relevant exposure pathways

Activity or type of material handled	Most relevant exposure pathway
Raw materials	External exposure to gamma radiation
Scale, incrustations, Ra type (geothermal, oil/gas)	External exposure to gamma radiation
Scale, incrustations, Pb type	Inhalation of dust
Processing residues	External exposure to gamma radiation
Slags, bottom ash	External exposure to gamma radiation
Filter dust of high temperature processes (Pb, Po)	Inhalation of dust
Underground mines, caves, museum mines, Rn spas	Radon
Water utilities	Radon
Welding with thoriated electrodes	Inhalation of dust
Natural gas transport and filters (Pb, Po)	Inhalation of dust

Adapted from occupational exposure study of NCC/BfS (2017), various Bavarian studies, industry studies

Study of radionuclide excretion of workers in NORM industries (2005)

- Detailed study by VKTA Dresden for German Office for Radiation Protection
- 104 test persons (probands)
- Workers from
  - Utilities (drinking water)
  - Natural gas producers
  - Radon spas
  - Underground museum mines
- Members of the general public
- Unfortunately, no dose calculations were included in the study

		Excretion rates (50 % Percentil)		
		All	Workers	General population
Matrix	Nuclid	[mBq/d]	[mBq/d]	[mBq/d]
Urine	^{226}Ra	7,5	6,6	8,1
	^{210}Pb	7,5	8,5	6,3
	^{210}Po	4,3	5,1	3,5
Faeces	^{230}Th	5,1	5,5	4,1
	^{226}Ra	32	37	21
	^{210}Pb	34	40	30
		Specific Activity [mBq/g] (50 % Percentil)		
Hair	^{226}Ra	<1	<1,0	<1,0
	^{210}Pb	5,8	7,2	3,2

St.Sch.-Nr.4280 VKTA

Abschlussbericht

2005

zum Forschungsvorhaben St.Sch.-Nr.4280

„Ermittlung der Zufuhr von natürlichen Radionukliden der Uranzerfallsreihe (^{230}Th, ^{226}Ra, ^{210}Pb, ^{210}Po) bei Personen aus der Bevölkerung, in belasteten Gebieten und Wohnungen und an NORM-Arbeitsplätzen durch Ausscheidungsanalyse"

Fördernde Institutionen:
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Summary (1)

- New European (hence, German) regulations require dose assessments at workplaces where increased doses may be expected
  - With the new law, radon at workplaces is subject to dose assessment
- Under new radiation protection law, the number of occupationally exposed workers in NORM sectors in the German dose register will increase by 20 to 60%
- Most relevant exposure pathways in NORM industries
  - Inhalation to dust
  - Direct exposure to gamma radiation
  - Exposure to radon

Summary (2)

- Simple Bq/g to mSv/a relationships are useful generic screening tools, but may not be sufficient in specific situations
- Understand the technological processes and hence the typical nuclide vector of materials involved
- Take represantative samples and measure at workplaces, do not rely on literature data alone
  - For example, use respiratory protection to realistically determine activity intake by dust inhalation
- Check plausibility of literature data and adapt to real situation
  - E.g., dust suppression measures such as wetting, encapsulation
  - Lower radon equilibrium factor near the source

Questions? Want to discuss further?

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European NORM Association

ENA working groups

- NORM in the industry
- NORM in the environment
- NORM in building materials