Effective dose coefficients for inhaled radon progeny:
ICRP's approach for workers

12th EURADOS Winter School

Lodz, Poland, February 2019

James Marsh, Public Health England, (PHE), UK

Dominique Laurier, Institut de Radioprotection et de Sûreté Nucléaire, (IRSN), France

Margot Tirmarche, coordinator of TG64, Authority for Nuclear Safety and Radiological Protection, (ASN), France

Structure of talk

1) Introduction

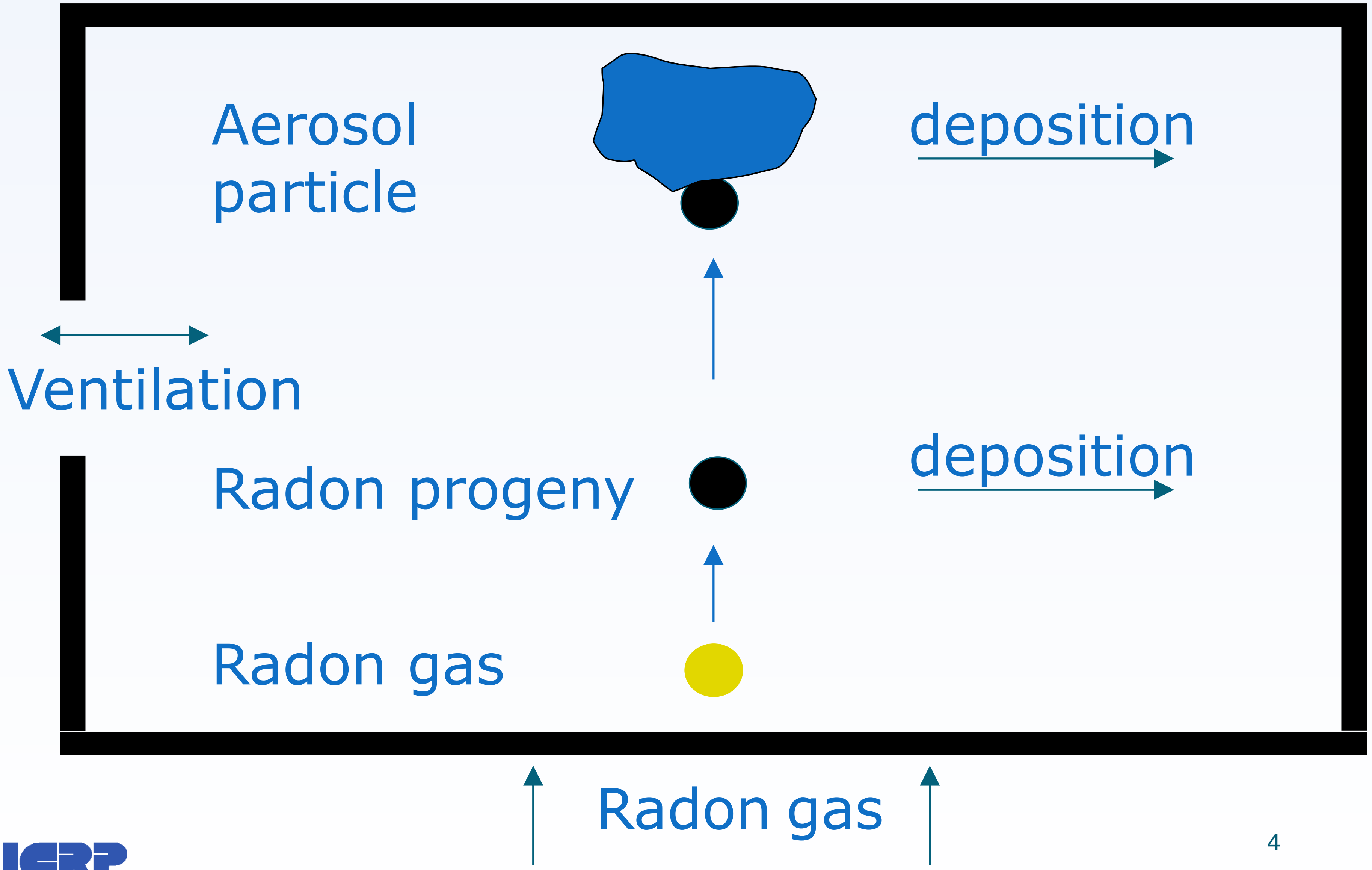
2) Dose coefficients, Sv per unit exposure
   - ➢ Epidemiological approach
   - ➢ Dosimetric approach

3) Management of radon in workplaces

Decay chain of U-238

		Half-life
Radon gas	$^{222}\mathrm{Rn}$	3.8 d
	↓	
Polonium	$^{218}\mathrm{Po}$	3 min
	↓ α	
Lead	$^{214}\mathrm{Pb}$	27 min
	↓	
Bismuth	$^{214}\mathrm{Bi}$	20 min
	↓	
	$^{214}\mathrm{Po}$	160 μs
	↓ α	
	$^{210}\mathrm{Pb}$	22 y

Formation of radon progeny aerosol



Aerosol particle

deposition

Ventilation

Radon progeny

deposition

Radon gas

Radon gas

INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

Equilibrium factor, *F*

F is a measure of the degree of dis-equilbrium between radon gas and its progeny

F=1

Nuclide	Bq m^{-3}
^{222}Rn gas	1.0
^{218}Po	1.0
^{214}Pb	1.0
^{214}Bi	1.0

F=0.4

Nuclide	Bq m^{-3}
^{222}Rn gas	1.0
^{218}Po	0.7
^{214}Pb	0.4
^{214}Bi	0.3

The value of *F* depends on the ventilation rate :

Indoors :	$F \approx 0.4$	Natural ventilation
Mines :	$F \approx 0.2$	Forced ventilation

Unattached fraction, f_p

f_{p} depends upon number of particles in the air

$$\mathbf{f_p} = \frac{\mathbf{414}}{\mathbf{z}}$$

Where Z is number concentration of aerosol (cm^{-3}) [Porstendörfer, 2001]

Indoors : $f_{\mathrm{p}} \approx$ 3% - 15%

Mines : $f_{\mathrm{p}} \approx$ 0.1% - 4%

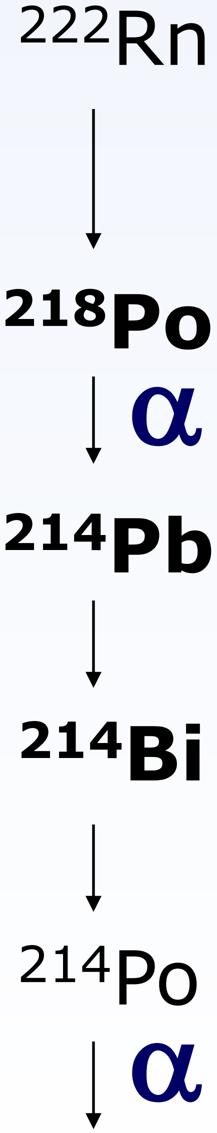
Quantities and Units (Concentration)

Activity concentration of radon.

- Measured in Bq m^{-3}

Potential Alpha Energy Concentration (PAEC)

- Working level
  - 1 Working Level (WL) is any combination of short lived radon progeny in 1 m^3 of air which will ultimately emit 1.3×10^8 MeV of alpha energy
  - 1 WL = 1.300×10^8 MeV m^{-3} or 2.08×10^{-5} J m^{-3}



^{222}Rn

^{218}Po

α

^{214}Pb

^{214}Bi

^{214}Po

α

Quantities and Units (Exposure)

Working Level Month (WLM)

1 WLM is an exposure to 1 WL for 1 month (170 h)

1 WLM = 3.54 mJ h m^{-3}

Annual average exposure of radon gas in a home of 230 Bq m^{-3} = 1 WLM

Radon gas exposure

Bq m^{-3} h

1 Bq m^{-3} h = F x 1.57 x 10^{-6} WLM

F is the equilibrium factor

ICRP Publications

Publication 65 (1993)	Protection against Radon-222 at home and at work
Publication 103 (2007)	Recommendations
Publication 115 (2010)	Lung Cancer Risk from Radon and Progeny + Statement on Radon
Publication 126 (2014)	Radiological Protection against Radon Exposure
Publication 137 (2017)	Occupational Intakes of Radionuclides, Part 3

Calculation of lifetime absolute risks (ICRP Publication 115)

- **Lifetime:** cumulative risk up to age 90 (ICRP, 1993)
- **Exposure scenario:** 2 WLM per year from age 18 - 64
- **Background rates, R_o:** ICRP reference population (ICRP, 2007)
  Euro-American/ Asian population
  Smoking included
- **Risk model:** (ERR per WLM) Obtained from miner epidemiological studies
  Time dependent modifying factors
- **Projection model:** multiplicative model

absolute risk, $R(w) = \mathbf{R_o}\ .(1 + \underset{\uparrow\ \text{ERR per WLM}}{\beta}\ .\ \underset{\uparrow\ \text{Exposure, WLM}}{w})$

Miner data : Lifetime Excess Absolute Risk

Reference	Risk model	Background rates, (ICRP reference population)	Risk x 10^{-4} WLM^{-1}
ICRP Pub. 65 (1993)	GSF model (ICRP Pub. 65)	ICRP Pub. 60 (Japan, USA, Puerto Rico, UK, China)	2.83
Tomasek *et al* (2008)	GSF model (ICRP Pub. 65)	ICRP Pub. 103 (Euro-American/ Asian population)	2.7
Tomasek *et al* (2008)	BEIR VI(a) (11 studies)	ICRP Pub. 103	**5.3**
	Czech-French	ICRP Pub. 103	**4.4**

A lifetime excess absolute risk of 5 10^{-4} per WLM is proposed for radiation protection purposes (ICRP, 115).

(a) Exposure-age-concentration risk model

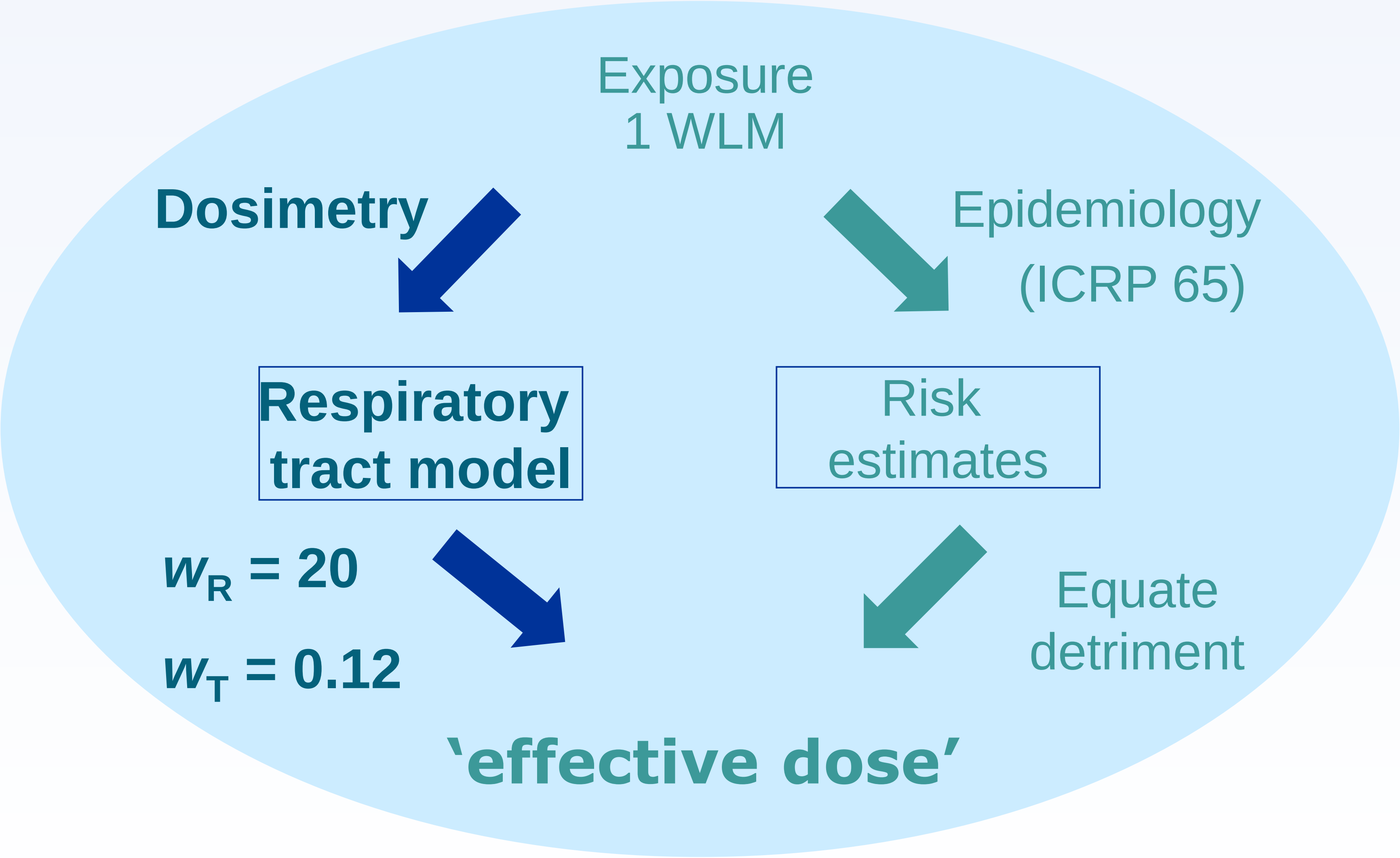
Conclusions of Publication 115 + Statement on Radon

- Revised nominal risk coefficient of **$5\ 10^{-4}$ WLM^{-1}** replaces the Pub 65 value of $2.83\ 10^{-4}$ WLM^{-1}

    ➢ Upper Reference Level for homes reduces from 600 Bq m^{-3} to 300 Bq m^{-3}

- Proposes to publish dose coefficients for radon and its progeny calculated using ICRP reference biokinetic and dosimetric models.

Dose conversions factors (effective dose per unit exposure)



Exposure
1 WLM

Dosimetry

Epidemiology

(ICRP 65)

Respiratory tract model

Risk estimates

$w_R = 20$

$w_T = 0.12$

Equate detriment

‘effective dose’

Epidemiological approach

$$\frac{Risk\ per\ WLM}{Risk\ (detriment)\ per\ Sv} = Sv\ per\ WLM$$

“Dose conversion convention” ICRP 65

Epidemiological approach - revised

USE revised value of 5×10^{-4} per WLM for the lung cancer risk

Equating total detriment using ICRP Publication 103 values

Workers	4.2×10^{-2} Sv^{-1}	12 mSv WLM^{-1}
Public	5.7×10^{-2} Sv^{-1}	9 mSv WLM^{-1}

Publication 65 values

Workers	5 mSv WLM^{-1}
Public	4 mSv WLM^{-1}

Radon progeny dosimetry
Intake

Intake is the total activity of a radionuclide entering the body from the external environment

<u>Exposure</u>

Concentration (Bq m^{-3})

x

Time (h)

X

Average Breathing rate

(m^{3} h^{-1})

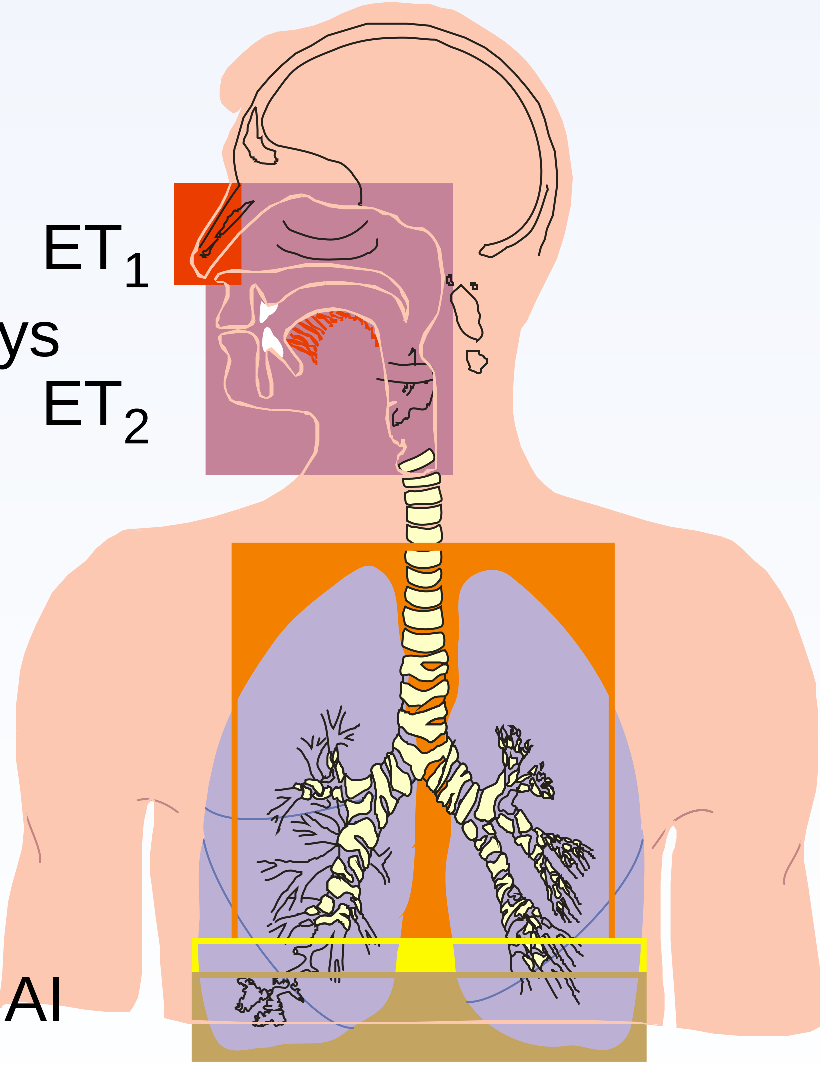
=

INTAKE (Bq)

$$\text{Bq.m}^{-3}\,\text{h} \quad \times \quad \text{m}^{3}\,\text{h}^{-1} \quad = \quad \text{Bq}$$

Radon dosimetry

Human Respiratory Tract Model (ICRP Publication 66)



ET_1

Extrathoracic airways

ET_2

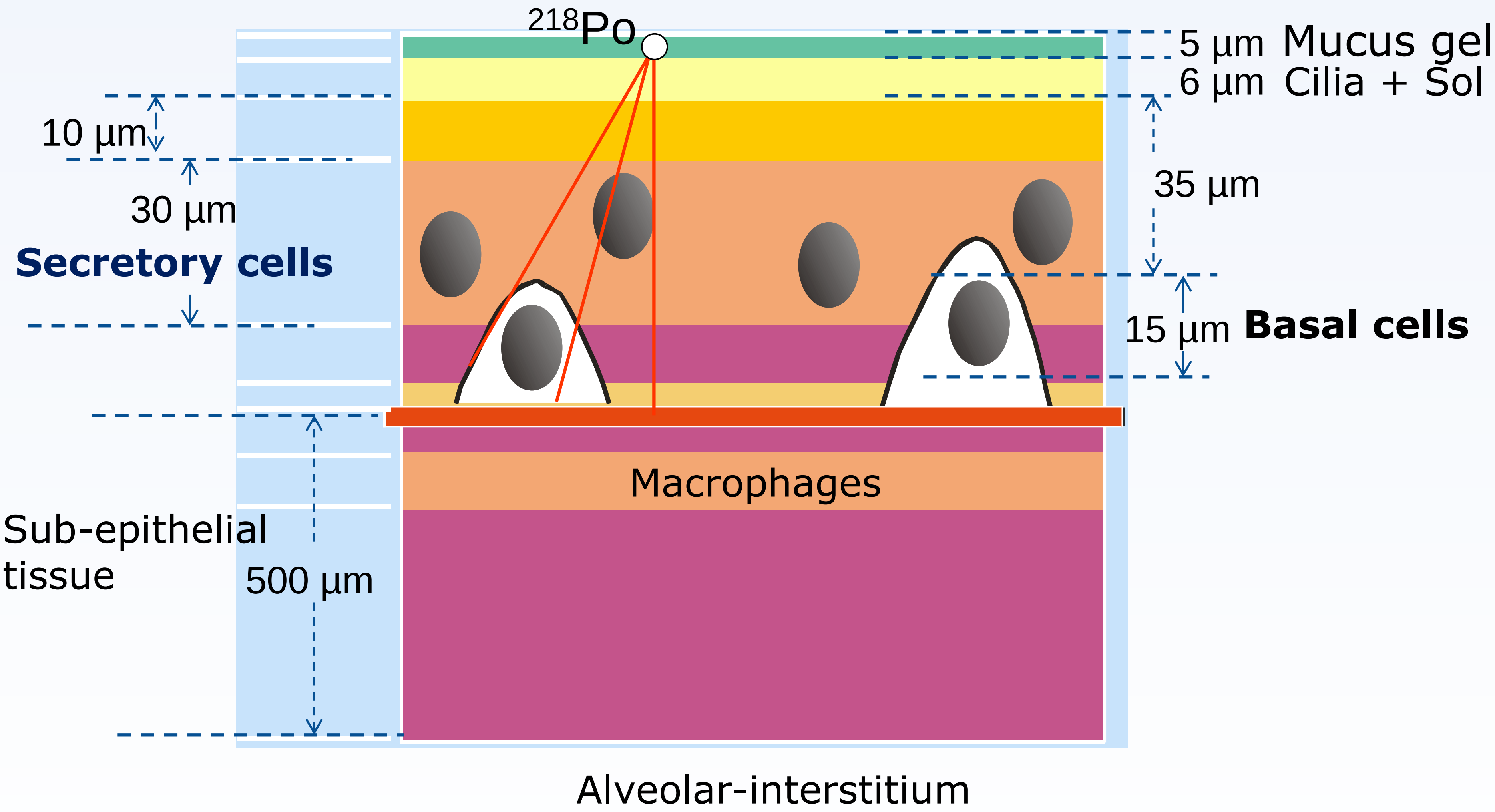
Bronchial, BB

Bronchiolar, bb

Alveolar interstitial, AI

	airway generations
BB	**0 - 8**
bb	**9 -15**
AI	

Bronchial (BB) wall dosimetry



Equivalent dose to lung, H_{lung}

Equivalent dose is calculated to each of the 3 regions

- bronchial region (BB): $H_{BB} = ½ (H_{bas} + H_{sec})$
- bronchiolar region (bb): H_{bb}
- Alveolar-Interstitial region (AI): H_{AI}

$$H_{lung} = H_{BB}\, A_{BB} + H_{bb}\, A_{bb} + H_{AI}\, A_{AI}$$

Where A_i = the apportionment factor representing the regional's estimated sensitivity to radiation induced lung cancer relative to that of whole lung.

Regional distribution of spontaneous lung cancers in general population is:
0.6 for BB; 0.3 for bb; 0.1 for AI (ICRP 66, para. 113)

$$A_{BB} = ⅓; \quad A_{bb} = ⅓; \quad A_{AI} = ⅓$$

Factors affecting dosimetric calculations per unit exposure

- Aerosol characteristics
  - Unattached fraction
  - Size distribution

Affects deposition in respiratory tract

- Breathing rate
  - Affects intake and deposition

- Equilibrium factor (if radon gas is measured)

Exposure conditions in mines

Aerosol characteristics depend on exposure conditions:

- Use of diesel or electrical powered equipment

- Ventilation rates

- Type of heating:

- Ventilation air is heated by burning propane gas

Drilling Machine

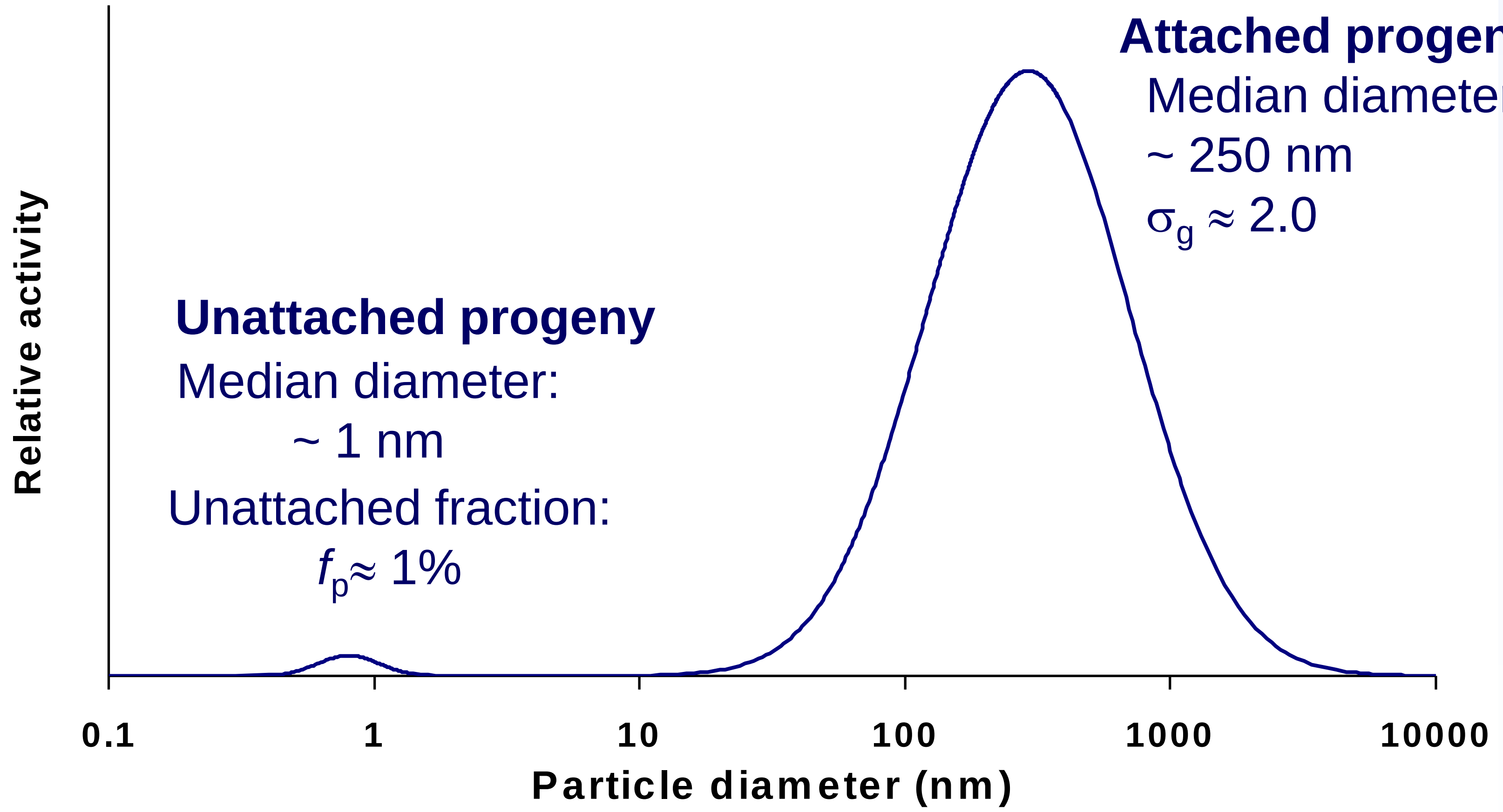
Diesel loading machine

Forced ventilation

Pictures from COGEMA (AREVA NC); Courtesy of IRSN

Activity size distribution of a radon progeny aerosol in a diesel-powered mine

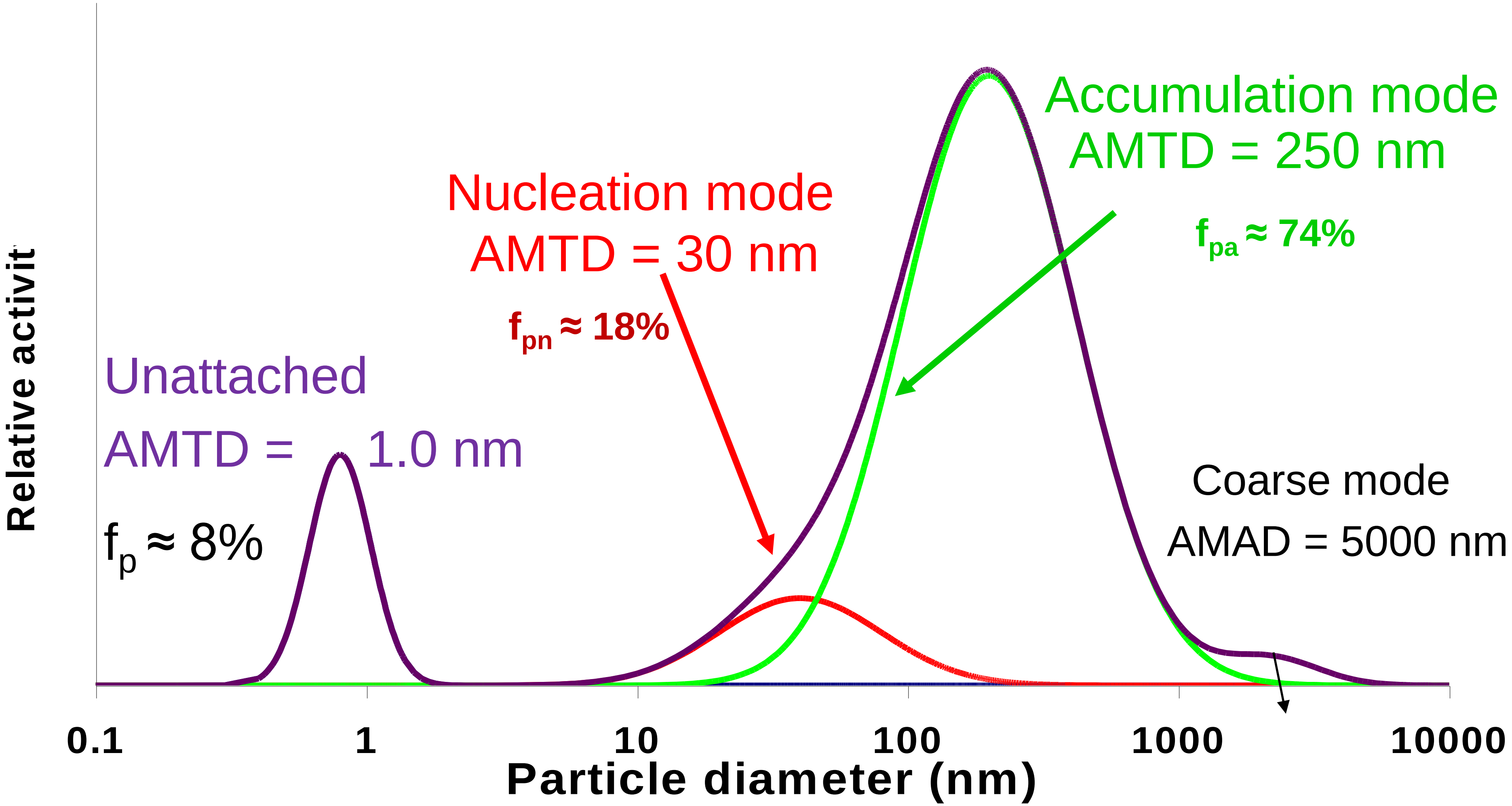
Based on measurements carried out in the early 1990s



Attached progeny
Median diameter:
~ 250 nm
$\sigma_g \approx 2.0$

Unattached progeny
Median diameter:
~ 1 nm
Unattached fraction:
$f_p \approx 1\%$

Activity size distribution : indoor workplace



Unattached

AMTD = 1.0 nm

$f_p \approx 8\%$

Nucleation mode

AMTD = 30 nm

$f_{pn} \approx 18\%$

Accumulation mode

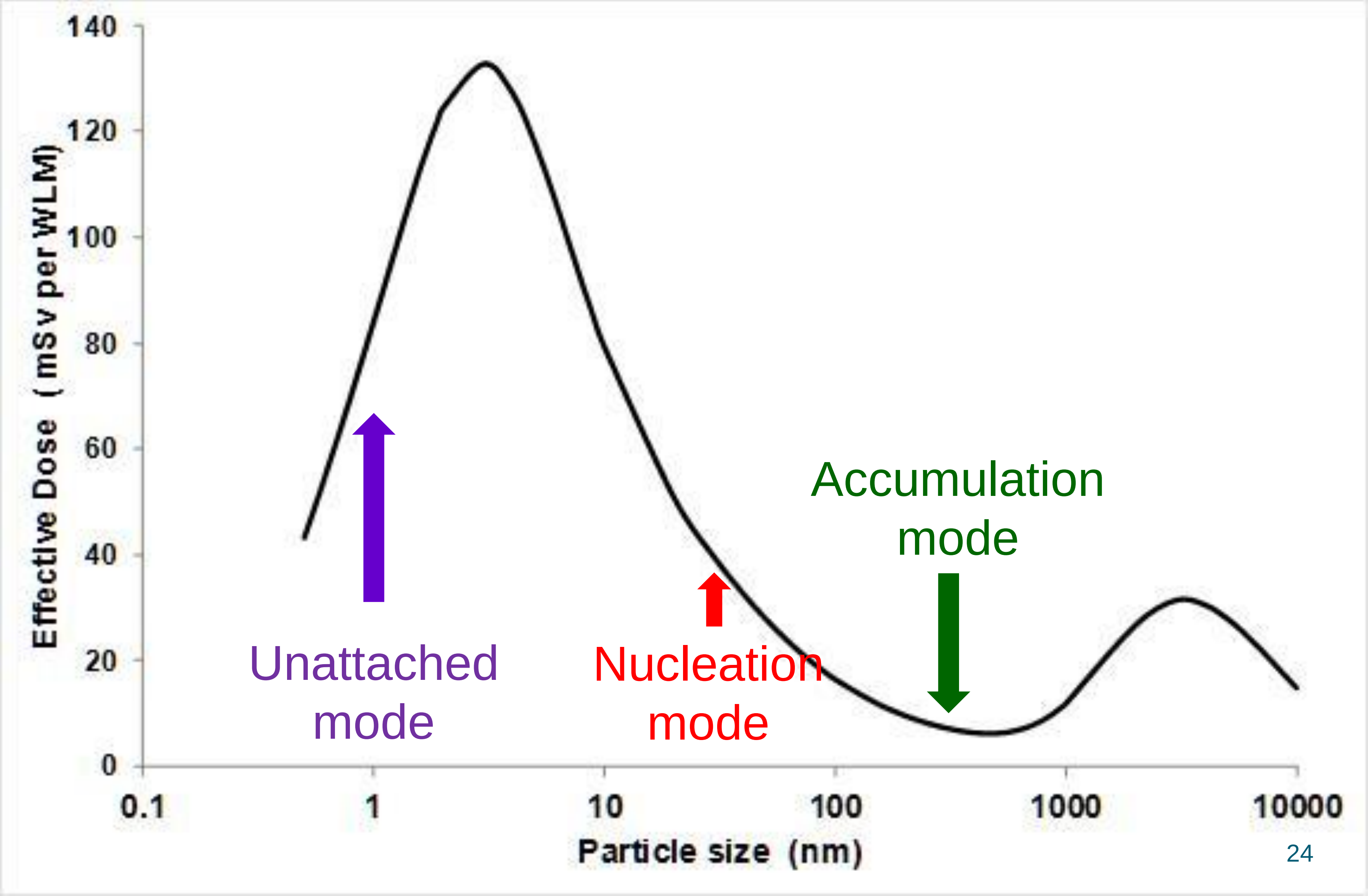
AMTD = 250 nm

$f_{pa} \approx 74\%$

Coarse mode

AMAD = 5000 nm

Effective dose per WLM as a function of particle size



Accumulation mode

Unattached mode

Nucleation mode

Equivalent dose to lung, H_{lung} for a miner

$$H_{lung} = ⅓\, H_{BB} + ⅓\, H_{bb} + ⅓\, H_{AI}$$

Region	**Absorbed dose mGy/WLM**	**Equivalent dose mSv/WLM**
Bronchial (BB)	6.7	134
Bronchiolar (bb)	7.0	140
Alveolar-Interstitial (AI)	0.4	8
Lung, H_{lung}		94

Effective dose ≈ w_T(lung) × H_{lung} = 0.12 × 94 mSv per WLM

= 11 mSv per WLM

(Marsh et al., 2012)

ICRP Dose coefficients for inhaled radon progeny – OIR Part 3

	Unattached fraction, f_p	Effective dose$^{(a)}$ (mSv per WLM)	
Mine	0.01	$[86.\ f_p + (1 - f_p).10]$	**11**
Indoor workplace	0.08	$[86.\ f_p + (1 - f_p).14]$	**20**
		Lower breathing rate$^{(b)}$	**14**
Tourist cave 	0.15	$[86.\ f_p + (1 - f_p).12]$	**23**

(a) ICRP reference breathing rate is 1.2 m^3 h^{-1} (⅓ sitting, ⅔ light exercise)

(b) Lower breathing rate of 0.86 m^3 h^{-1} (⅔ sitting, ⅓ light exercise)

Comparison between dosimetry and epidemiological approaches

	Effective dose	
	mSv per WLM	mSv per mJ h m^{-3}
Dosimetry		
Mine	**11**	**3.1**
Indoor workplace	20	5.6
Lower breathing rate	14	3.9
Home	13	3.6
Tourist Cave	23	6.6
Epidemiology		
Workers	**12**	**3.4**
Public	**9**	**2.6**

1 WLM = 3.54 mJ h m^{-3}

Approach adopted

Occupational Intakes of Radionuclides (OIR), Part 3; ICRP Publication 137

- For the calculation of doses to **workers** following exposure to radon (^{222}Rn) and radon progeny in **mines and most buildings**, the Commission recommends a rounded dose coefficient of:
    - **3 mSv per mJ h m^{-3}** (11 mSv per WLM)

- For **workers in tourist caves** and **indoor workers engaged in substantial physical activity**, the Commission recommends a rounded dose coefficient of:
    - **6 mSv per mJ h m^{-3}** (21 mSv per WLM)

Approach adopted

Occupational Intakes of Radionuclides (OIR), Part 3; ICRP Publication 137

- Adjustments for aerosol characteristics are not warranted for most exposure situations.

  - ➢ However, where reliable aerosol data are available, site-specific dose coefficients can be calculated using the information provided in OIR part 3.

    → Only if approved by the regulator.

Aerosol measurements in a mine (2013)

Multiscreen continuous diffusion battery

Courtesy of Stephen Solomon, ARPANSA, Australia

Recent aerosol measurements at a uranium mine in Australia (Solomon et al., 2018)

Exposure scenario	**Unattached fraction, f_p**	**Attached aerosol characteristics**			**Effective dose coefficient (mSv/WLM)**
		Mode	**Fraction of attached PAEC, f_{pi}**	**Size, AMTD (nm)**	
Operational areas of mine with high levels of PAEC					
Exploration site	0	Nuc. Acc.	0.1 0.9	30 190	**14**
Drilling site	0	Nuc. Acc.	0.33 0.67	40 180	**17.5**
High ventilation rates with lower levels of PAEC					
Auto. Workshop	0.28	Acc.	1.0	160	**23**
Drill workshop	0	Nuc. Acc.	0.46 0.53	30 270	**23**

Calculation of effective dose from radon gas measurements

$$Annual\ effective\ dose\ (mSv) = \boldsymbol{DCF} \times 5.56 \times 10^{-6} \sum_i \left(C_{Rn_i} \times F_i \times \boldsymbol{O_i} \right)$$

Dose conversion factor; mSv per mJ h m^{-3}

Annual average radon concentration; Bq m^{-3}

Occupancy; hours per year

- In most cases use *DCF*= 3.0 mSv per mJ h m^{-3} and *F*=0.4.
  - ➢ 6.7×10^{-6} mSv per h Bq m^{-3}
- In cases where *F* is small and has been determined by measurement then
  - ➢ also measure f_p and calculate *DCF*
  - ➢ otherwise assume *F*=0.4

Radiological protection against radon exposure (ICRP Publication 126)

- Based on setting reference levels and applying optimisation.
  - Upper Reference Level (URL) of 300 Bq m^{-3} is recommended for **all workplaces** and homes

Place	Occupancy (h per year)	Effective dose at the URL (mSv per year)[a]
Most indoor workplaces	2000	4
Tourist caves Indoors + physical activity	2000	8
Homes	7000	14

(a) Assumes F=0.4

- **A specific graded approach is recommended for workplaces**

European directive (2013/59/EURATOM)

1. Measure radon in workplaces:
   - If in a radon prone area *[Article 54(2)a]*
   - Of a certain type; e.g. schools, workplaces with occupied basements, underground workplaces *[Article 54(2)b]*

2. Optimise below the NRL (< = 300 Bq m-3) *[Article 7(1)]*

3. If despite actions taken the radon level as an **annual average** continue to exceed NRL then
   - Notify relevant regulator *[Article 54(3)]*
   - Carry out a dose assessment

European directive (2013/59/EURATOM)

4. If doses > 6 mSv per year:
   - ➢ Manage as a planned exposure situation *[Article 35(2)]*
   - ➢ Relevant national requirements must be met

5. If doses ≤ 6 mSv per year:
   - ➢ Exposures kept under review *[Article 35(2)]*

- ***Doses Assessment***
  - ➢ Occupancy
  - ➢ Annual average radon concentrations during occupancy
    - – Appropriate, if variations are regular
    - – Time-resolved measurements

Annual dose reference level

Effective dose of 6 mSv per year corresponds to an average radon concentration of:

- **450 Bq m^{-3}**
  - effective dose coefficient of 3.0 mSv per mJ h m^{-3}
  - appropriate for most indoor workers.

- **225 Bq m^{-3}**
  - effective dose coefficient of 6.0 mSv per mJ h m^{-3}
  - appropriate for tourist caves and indoor workers engaged in substantial physical activity.

Assuming an occupancy of 2000 h y^{-1} *and F*=0.4

Summary points

- Strong epidemiological evidence that inhalation of ^{222}Rn progeny can cause lung cancer.
  - Good consistency between risk estimates from miner and indoor studies.

- Revised nominal risk coefficient has almost doubled to 5×10^{-4} WLM^{-1}.

- A specific graded approach for control of radon in workplaces
  - URL of 300 Bqm^{-3} → measurement → optimisation
  - dose assessment

Summary points

- For occupational exposure, the revised dose coefficients are:
  - **3 mSv per mJ h m^{-3}** (11 mSv per WLM)

    → for mines and most indoor workplaces
  - **6 mSv per mJ h m^{-3}** (21 mSv per WLM)

    → for tourist caves and indoor workers engaged in substantial physical activity
- ICRP has provide data for specific dosimetric calculations {ICRP Publication 137, (2017)}.

Acknowledgements

John Harrison,

Chair of ICRP Committee 2

Stephen Solomon,

Australian Radiation Protection and Nuclear Safety (ARPNS)

Christopher Clement

ICRP Scientific Secretary

Tim Fell and Demetrio Gregoratto

Public Health England, PHE

Thank you for your attention

www.icrp.org

www.ICRP.org

Quantities

Potential Alpha Energy Concentration (PAEC)

The concentration of any mixture of short-lived radon progeny in terms of the total alpha energy emitted during complete decay to stable ^{210}Pb. **Units: J m^{-3}**

Unattached fraction

The fraction of the potential alpha energy concentration (PAEC) of the short-lived radon progeny that is not attached to the ambient aerosol.

Equilibrium factor, F

It is the ratio of PAEC of for the actual radon progeny mixture to that which would apply at equilibrium.

$$F = \frac{PAEC\ of\ actual\ mixture}{PAEC\ if\ F=1}$$

^{222}Rn

↓

^{218}Po

↓ α

^{214}Pb

↓

^{214}Bi

↓

^{214}Po

↓ α