Institut de Tècniques Energètiques inte
UPC UNIVERSITAT POLITÈCNICA DE CATALUNYA

CURSO FORMACIÓN
EL RADÓN: EXPOSICIÓN DE RIESGO PARA LA SALUD. SOLUCIONES PARA SU REDUCCIÓN

ESTIMACIÓN DE LAS DOSIS DEBIDAS A LA INHALACIÓN DE LOS DESCENDIENTES DEL RADÓN: EL MODELO DOSIMÉTRICO DEL PULMÓN DE LA ICRP PARA EL CÁLCULO DE LA DOSIS

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Universidad de Santiago de Compostela 2010

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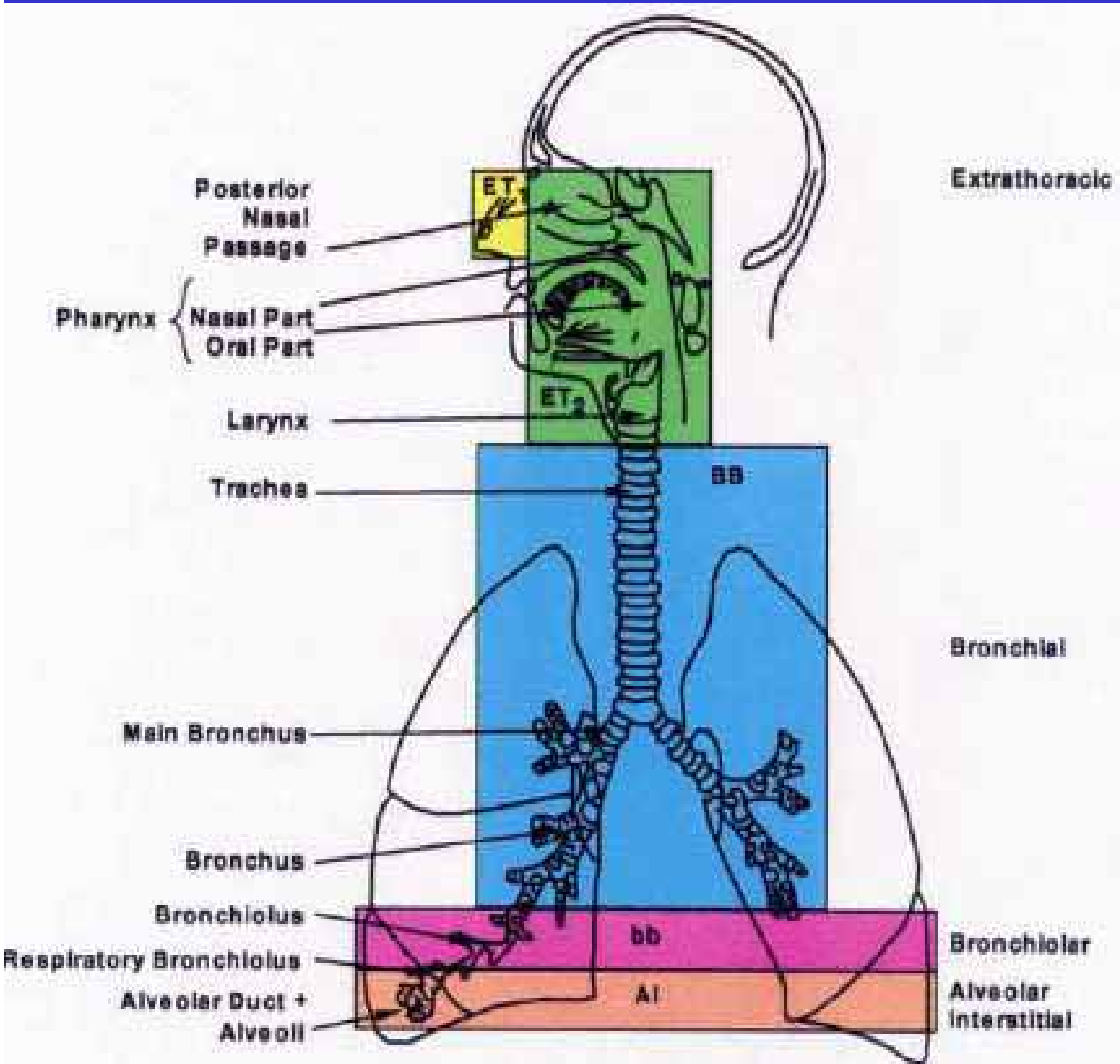
RIESGO RADIOLÓGICO. MODELO ICRP 66 (1994)



En función de las **propiedades físico-químicas** de las partículas, de la **fisiológica** del sistema respiratorio y de la características en la **respiración**, los descendientes del radón se depositan en las distintas regiones del tracto respiratorio.

Las regiones del sistema respiratorio tienen distinta **radiosensibilidad** debido a la diferencia fisiología y celular.

Magnitudes dosimétricas (ICRP 103)

La dosis absorbida es el cociente de la energía media depositada en un elemento de masa dm

$$D = \frac{d\overline{\varepsilon}}{dm}$$

Unidad: Gy (J kg^{-1})

Dosis absorbida promedio o dosis absorbida en un órgano o tejido:

$$D_T = \frac{1}{m_T} \int_{m_T} D \cdot dm$$

Unidad: Gy (J kg^{-1})

Dosis equivalente en un órgano o tejido, valora la eficacia biológica relativa de cada tipo de radiación.

$$H_T = \sum_R w_R \, D_{T,R}$$ Sv (J kg^{-1})

Tipo y rango energético	Factores de ponderación, w_R
Fotones (cualquier energía)	1
Electrones (cualquier energía)	1
Neutrones E< 10 keV	5
Neutrones 10 keV < E < 100 keV	10
Neutrones 100 keV < E < 2 MeV	20
Neutrones 2 MeV < E < 20 MeV	10
Neutrones E> 20 MeV	5
Protones E> 2 MeV	5
Partículas alfa	20

La dosis efectiva, es la suma de las dosis equivalentes ponderadas en todos los órganos y tejidos del organismo.

$$E = \sum_T w_T \, H_T = \sum_T w_T \sum_R w_R \, D_{T,R}$$

Sv (J kg^{-1})

Tejidos u órganos	w_T
Gónadas	0,20
Médula ósea (roja)	0,12
Colon	0,12
Pulmón	0,12
Estómago	0,12
Vejiga	0,05
Mama	0,05
Hígado	0,05
Esófago	0,05
Tiroides	0,05
Huesos (superficies óseas)	0,01
Piel	0,01
Resto(1)	0,05

Magnitud operacional para dosis por contaminación interna

- Dosis equivalente comprometida en un órgano o tejido, $H_T(\tau)$

$$H_T(\tau) = \int_{t_0}^{t_0+\tau} \dot{H}_T(t)\mathrm{d}t$$

Dosis efectiva comprometida, E (τ)

$$E(\tau) = \sum_{\mathrm{T}} w_{\mathrm{T}} H_{\mathrm{T}}(\tau)$$

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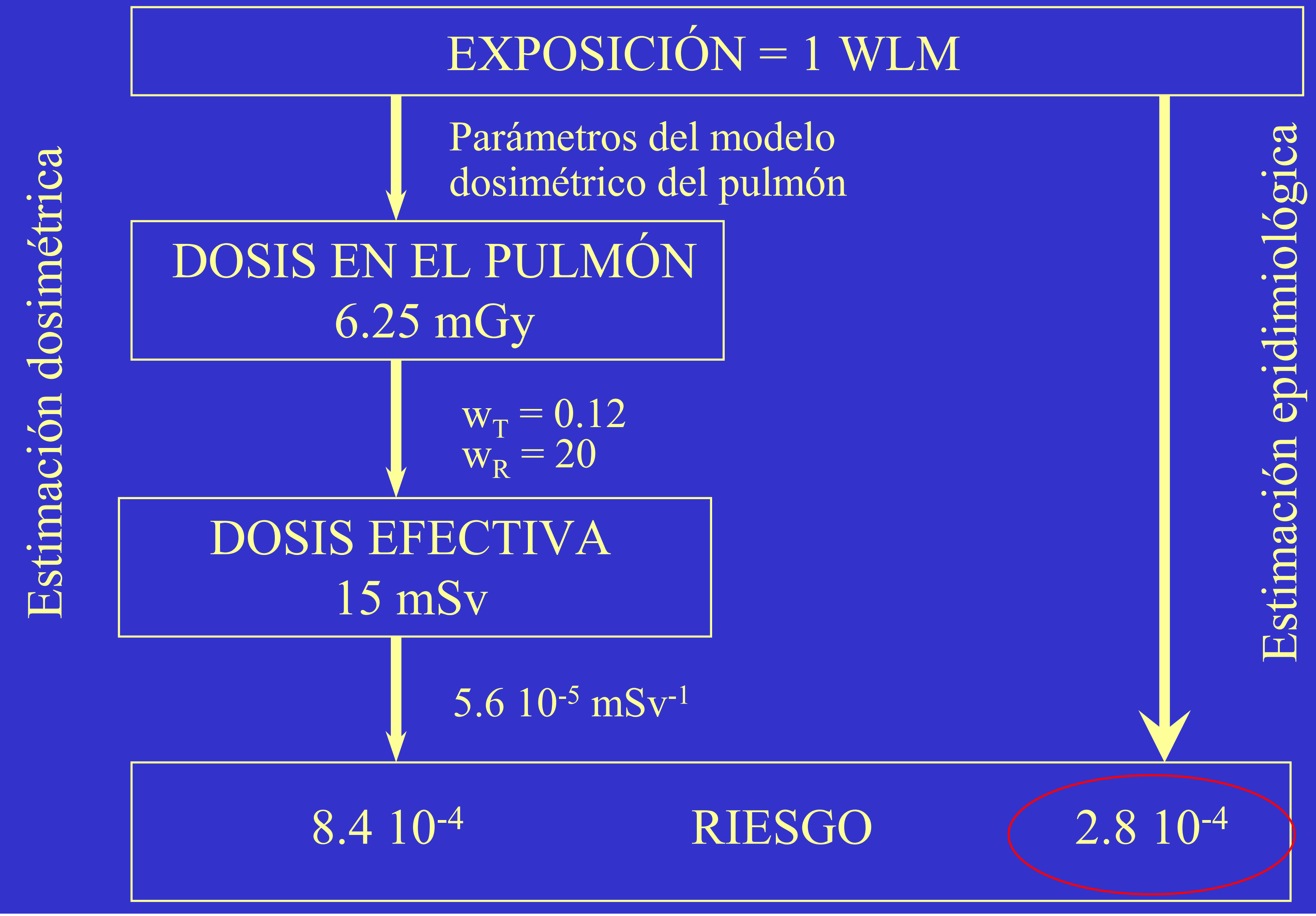
Comparación estimación riesgo cáncer de pulmón en mineros 1994



Birchall y Marsh (2005) 15 mSv por WLM → 12.5 mSv por WLM

DOSIMÉTRICO RIESGO: 8.4 10^{-4} por WLM → 7.0 10^{-4} por WLM

ICRP "Assessment and control of lung cancer risk from radon" (2010) draft

Realiza una revisión de los estudios epidemiológicos en mineros, incluyendo estudios con exposiciones bajas

EPI RIESGO: 2.8 10^{-4} por WLM → 5.0 10^{-4} por WLM

Realiza una revisión de los estudios caso-control en viviendas, considerando las incertidumbre aleatorias en las medidas

RIESGO (ERR): 1.08 por 100 Bq m^{-3} → 1.16 por 100 Bq m-3

Es consistente utilizar el modelos dosimétrico para el cálculo del riesgo debido a la inhalación de descendientes del radón

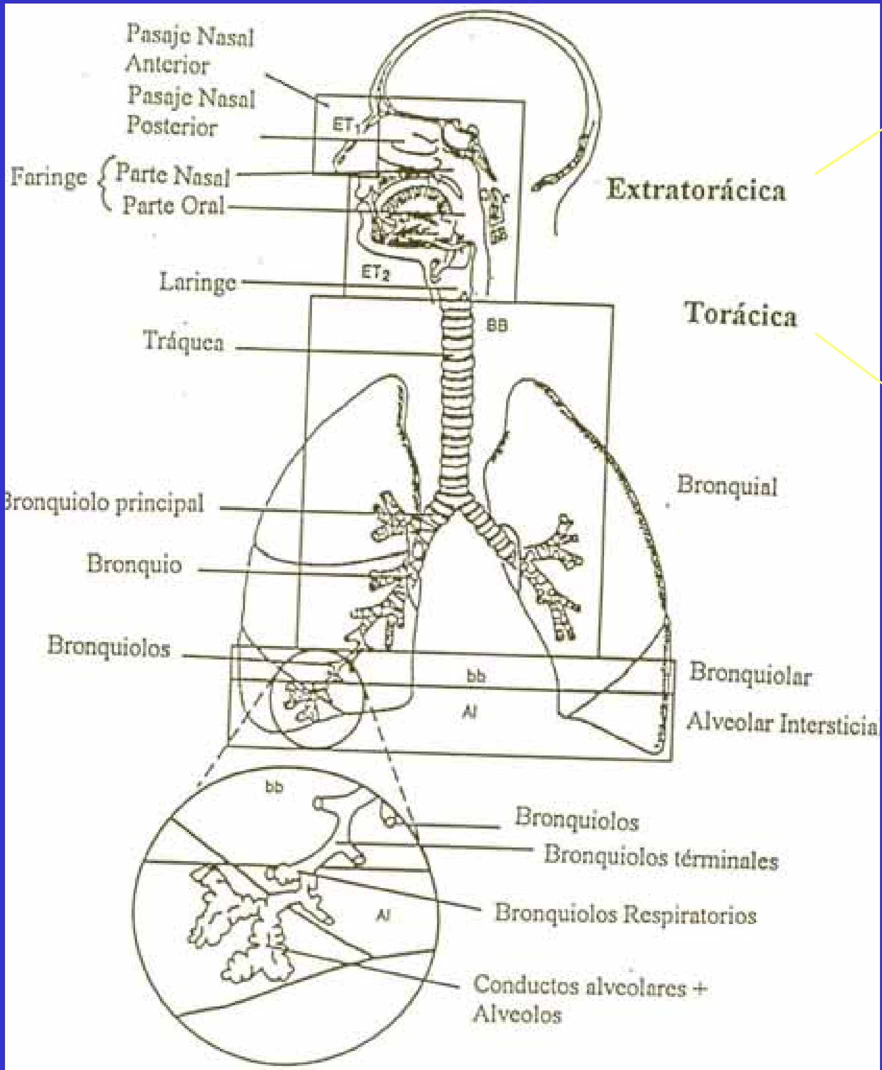
MODELO BIOCINÉTICO DEL TRACTO RESPIRATORIO SEGÚN ICRP 66

MODELOS DOSIMÉTRICO DE LAS VÍAS RESPIRATORIAS

MODELO ICRP 66 CONSTA DE 6 ELEMENTOS

1) MORFOMETRÍA: Describe la estructura y dimensiones del sistema respiratorio.
2) FISIOLOGÍA: Tasas de respiración y volúmenes de aire inhalados.
3) DEPOSICIÓN: Caracteriza la distribución inicial de partículas en las diferentes regiones anatómicas del sistema respiratorio.
4) ELIMINACIÓN: Evalúa aquellas partículas del sistema respiratorio que son eliminadas por transporte y absorción en la sangre.
5) RADIOBIOLOGÍA: Investiga los efectos biológicos de la radiación en las células de los tejidos del sistema respiratorio.
6) DOSIMETRICO: Evalúa la energía absorbida por unidad de masa en los tejidos del sistema respiratorio.

MODELO MORFOLÓGICO

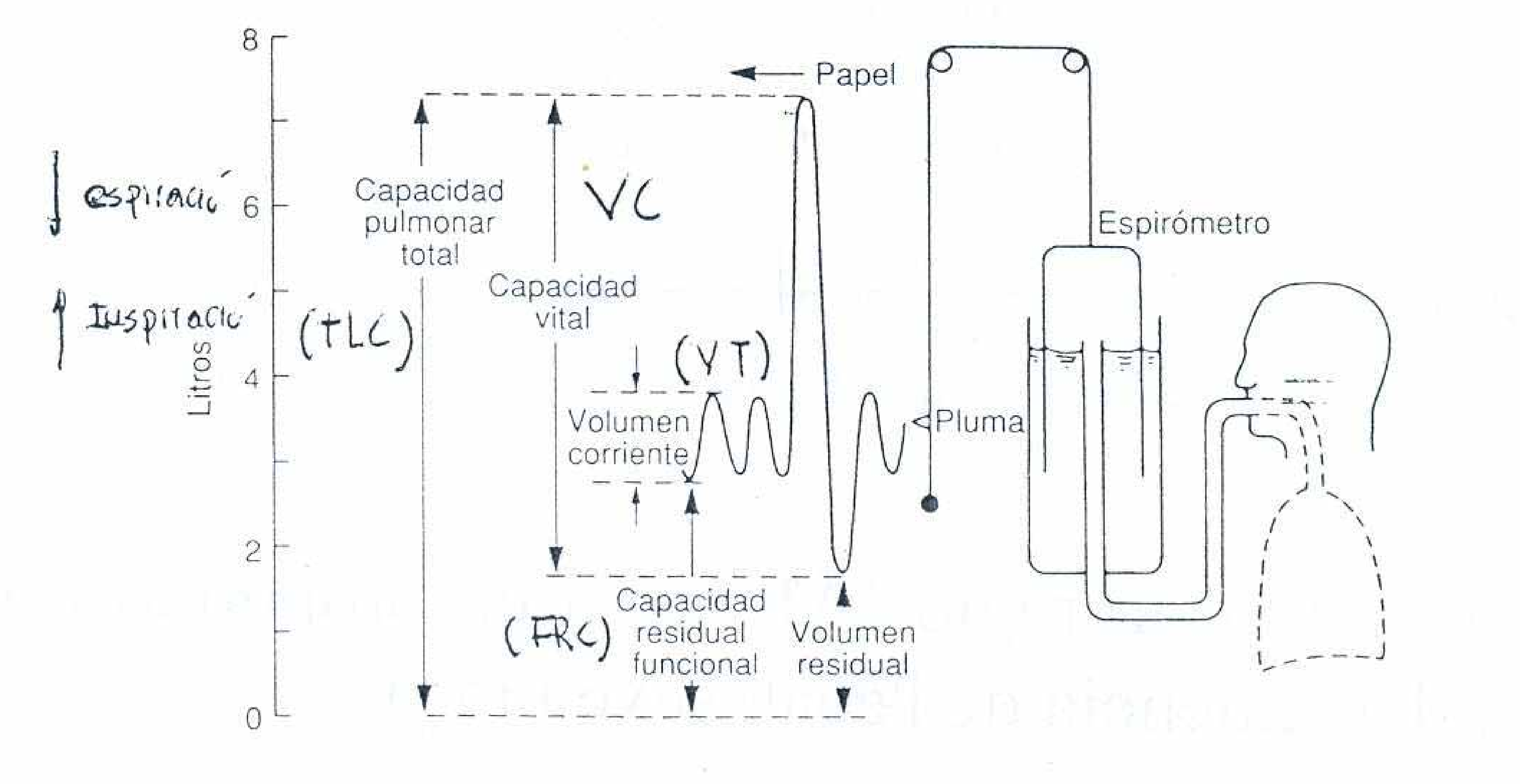


REGIÓN EXTRATORÁCICA
ET_1: naríz y pasajes nasales anteriores
ET_2: pasajes nasales posteriores, faringe y laringe

REGIÓN TORÁCICA (pulmones)
BB: tráquea, bronquios principales (primera bifurcación) y bronquios (hasta la generación 8ª del árbol pulmonar)
bb: bronquiolos (del la generación 9ª a la 15ª del árbol pulmonar)
AI: alvéolos e intersticios alveolares (de la generación 16ª hasta la última que suele ser la 18-20ª)

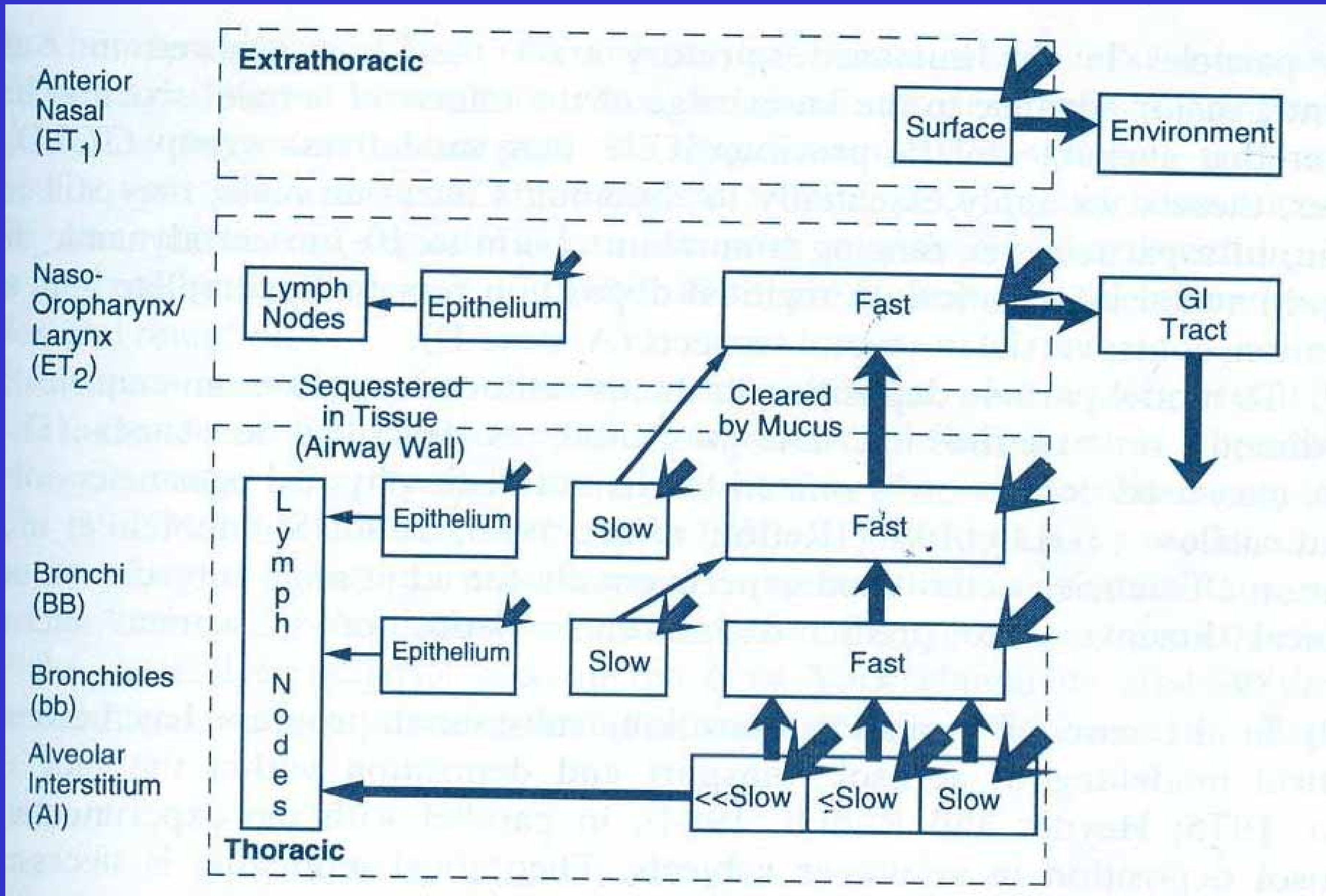
MODELO FISIOLÓGICO

Definiciones de parámetros fisiológicos utilizados en el cálculo dosimétrico



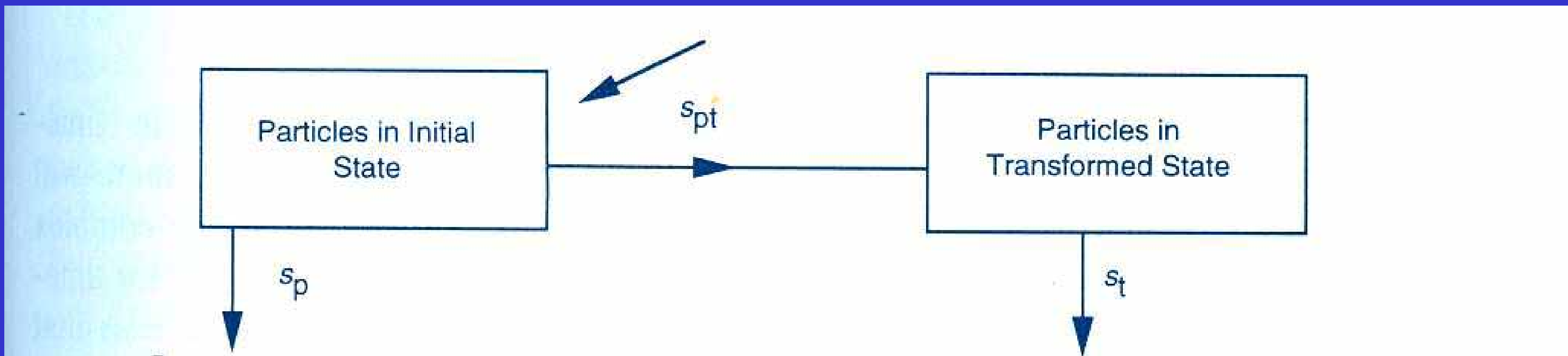
MODELO DE DEPOSICIÓN

Compartimentos del tracto respiratorio en los que las partículas pueden depositarse inicialmente. Se observan distintos compartimentos para una misma región debido a las variaciones temporales de transporte.

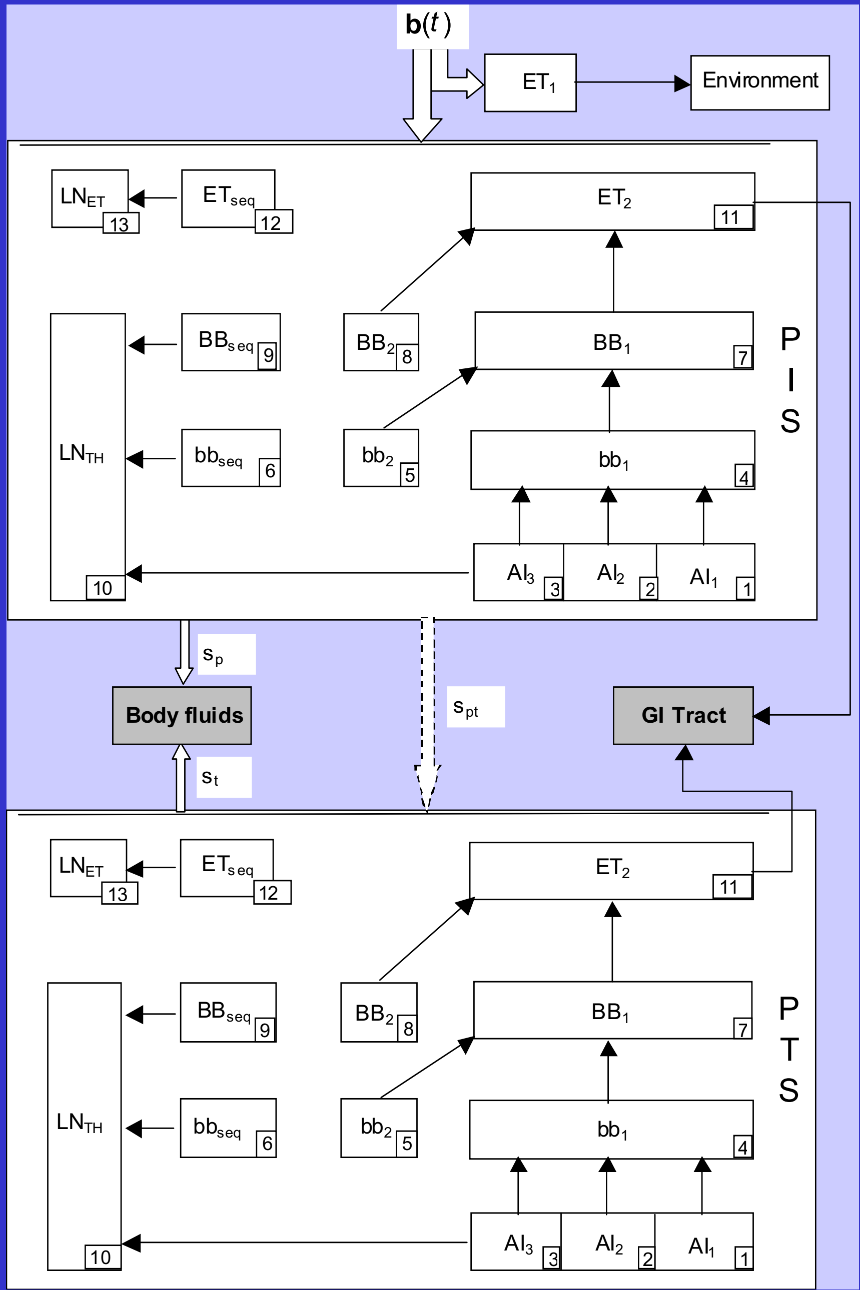


MODELO DE ABSORCIÓN EN LA SANGRE

Default absorption pa[redacted]rs	s	F	M	S
Initial disolution rate [redacted]	s_p	100	10	0.1
Transformation rate [redacted]	s_{pt}	0	90	100
Transformation rate [redacted]	s_t	0	0.005	0.0001



MODELO DE TRANSPORTE



MODELO DOSIMETRICO

Evalúa la dosis en cada uno de los tejidos que presentan riesgo radiológico

La dosis equivalente a un órgano o tejido T se calcula como la dosis equivalente instantánea integrada a lo largo de un periodo de tiempo t_1

$$H_T(t_1) = \int_0^{t1} \sum_s \sum_j q_{s,j}(t)\ SEE(T \leftarrow S; t)_j$$

donde

$q_{s,j}$ (t) es la actividad en Bq del radionucleido j en el órgano s en el instante t

SEE(T←S; t) es la energía absorbida por unidad de masa en el órgano T, y se expresa en Sv/s por Bq. La expresión para su cálculo es:

$$SEE(T \leftarrow S) = 1.6\,10^{-13}\ \frac{1}{m_T} \sum_R w_R\ Y_R\ E_R\ AF(T \leftarrow S; t)_R$$

donde

w_R es el factor de ponderación de la radiación R

Y_R es el rendimiento de la radiación R por trasformación nuclear en $(Bq\ s)^{-1}$

E_R es la energía de la radiación R en MeV/transformación

$AF(T \leftarrow S; t)_R$ es la fracción de energía emitida en S de la radiación R que es absorbida en el tejido T en el instante t

m_T es la masa del órgano o tejido en kg

MODELO RADIOBIOLÓGICO

Se trata de identificar los tejidos y células sujetas a riesgo radiológico y evaluar sus sensibilidades relativas

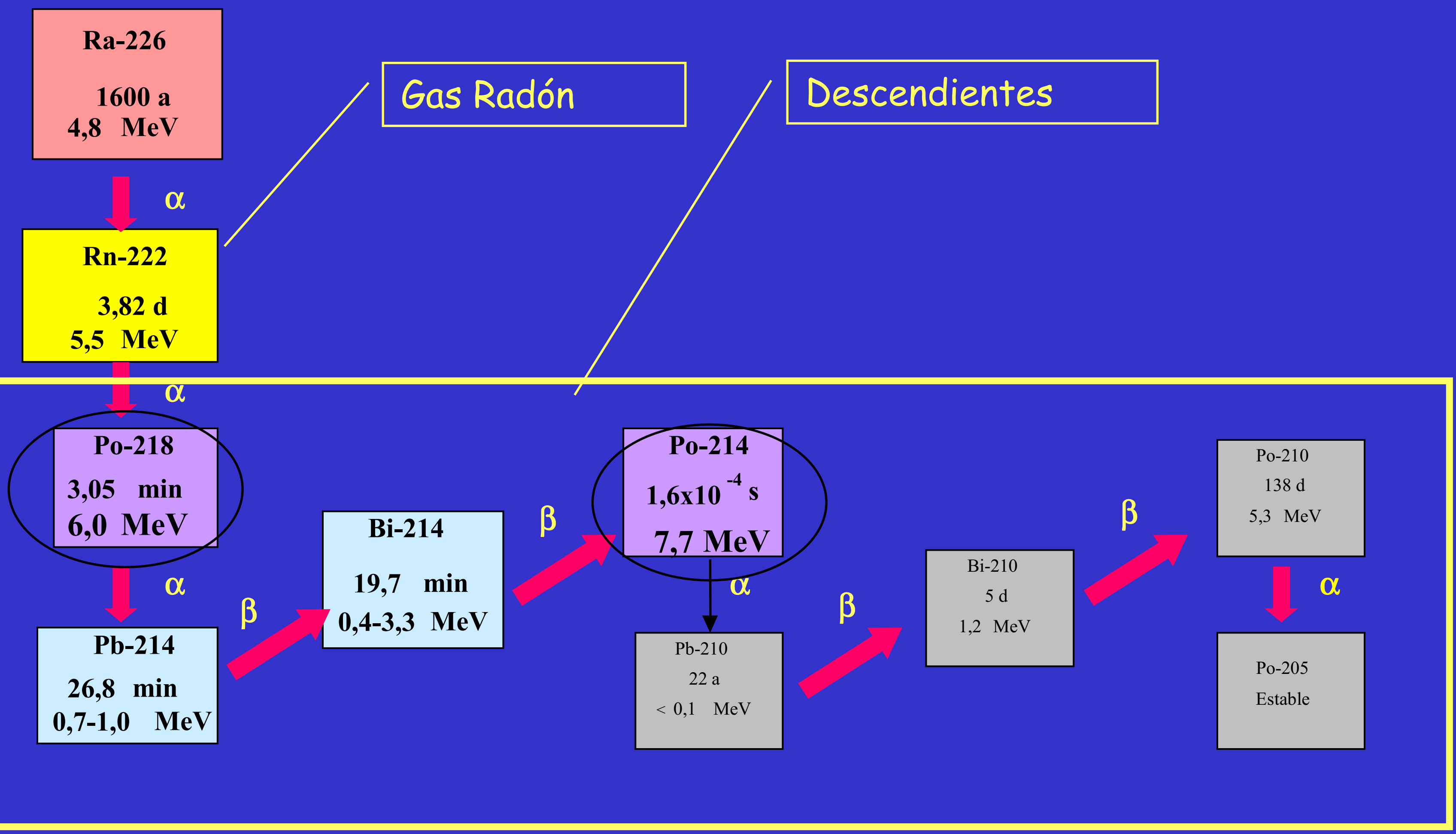
Se recomiendan los factores de ponderación para la dosis absorbida en cada uno de los tejidos y así, obtener un valor de dosis para la región extratorácica y otro para la torácica con el objetivo de ser utilizados en el cálculo de la dosis efectiva

Factores de ponderación asignados (A) a los tejidos del tracto respiratorio

Tissue	Assigned fractions (A) of w_T
Extrathoracic region	
ET_1 (anterior nose)	0.001
ET_2 (posterior nasal passages, larynx, pharynx, and mouth)	1
LN_{ET} (lymphatics)	0.001
Thoracic region	
BB (bronchial)	0.333
bb (bronchiolar)	0.333
AI (alveolar-interstitial)	0.333
LN_{TH} (lymphatics)	0.001

$$H_{TH} = H_{BB} A_{BB} + H_{bb} A_{bb} + H_{AI} A_{AI} + H_{LNTH} A_{LNTH}$$

CADENA DE DESINTEGRACIÓN U-238



MAGNITUDES Y UNIDADES DEL RADÓN

- **Energía potencial alfa (ε_p) (PAE):** es la energía alfa total emitida en la desintegración de un descendiente del radón en su cadena de desintegración hasta el Pb-210. Para la cadena del radón su expresión es:

			Energía potencial alfa				
			por átomo (E_{pj})		por Bq (E_{aj})		
Radionucleido	**j**	**$T_{1/2}$**	**MeV**	**10^{-12} J**	**MeV**	**10^{-10} J**	**k_{pj}**
^{222}Rn (Rn)	0	3,8 d	19,2	3,07	$9{,}2\ 10^{6}$	1470	----
^{218}Po (RaA)	1	3,05 min	13,7	2,19	3620	5,79	0,105
^{214}Pb (RaB)	2	26,8 min	7,7	1,23	17800	28,6	0,516
^{214}Bi (RaC)	3	19,7 min	7,7	1,23	13100	21,2	0,379
^{214}Po (RaC’)	4	164 µs	7,7	1,23	$2\ 10^{-3}$	$2{,}9\ 10^{-6}$	$6\ 10^{-8}$
Total (en equilibrio), por Bq de radón					34710	55.6	

$$\varepsilon_p\,(J) = [(6.0+7.7)\,N_{Po\text{-}218} + 7.7\,(N_{Pb\text{-}214} + N_{Bi\text{-}214})) +$$
$$+\,7.7\,N_{Po\text{-}214}]\ \cdot 1.602\ 10^{-13}$$

- **Concentración de energía potencial alfa (C_p) (PAEC):** es la concentración de una mezcla de descendientes en el aire en términos de energía potencial alfa por unidad de volumen. Siendo C = (N λ)/V Bq/m^3, se obtiene

$$C_p\ (J/\ m^3) = (5.79\ C_{Po\text{-}218} + 28.6\ C_{Pb\text{-}214} + 21.2\ C_{Bi\text{-}214})\ 10^{-10}$$

$$C_p\ (MeV/\ m^3) = 3615\ C_{Po\text{-}218} + 17840\ C_{Pb\text{-}214} + 13250\ C_{Bi\text{-}214}$$

La unidad clásica de C_p es el **working-level (WL)** : se define como una combinación de descendientes del radón de vida corta en 1 m^3 de aire que libera una energía potencial alfa de $1.30 \cdot 10^8$ MeV/m^3, equivalente a un valor de $2.08 \cdot 10^{-5}$ J/m^3.

$$1\ WL = 1.30 \cdot 10^8\ MeV/m^3 = 2.08 \cdot 10^{-5}\ J/m^3$$

➤ Concentración equivalente en equilibrio C_{eq}:

es aquella concentración de gas radón que estando en equilibrio con sus descendientes tiene la misma energía potencial alfa que la mezcla de descendientes en el aire

$$C_{ep}\ (Bq/\ m^3) = 0.105\ C_{Po\text{-}218} + 0.516\ C_{Pb\text{-}214} + 0.379\ C_{Bi\text{-}214}$$

$$1\ Bq/\ m^3 = 55.6\ 10^{-10}\ J/m^3 = 34710\ MeV/\ m^3 = 26.73\ 10^{-5}\ WL$$

$$1\ WL = 3740\ Bq\ m^{-3}$$

			Energía potencial alfa				
			por átomo (E_{pj})		por Bq (E_{aj})		
Radionucleido	**j**	**$T_{1/2}$**	**MeV**	**10^{-12} J**	**MeV**	**10^{-10} J**	**k_{pj}**
^{222}Rn (Rn)	0	3,8 d	19,2	3,07	9,2 10^6	1470	----
^{218}Po (RaA)	1	3,05 min	13,7	2,19	3620	5,79	0,105
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^{214}Bi (RaC)	3	19,7 min	7,7	1,23	13100	21,2	0,379
^{214}Po (RaC')	4	164 µs	7,7	1,23	2 10^{-3}	2,9 10^{-6}	6 10^{-8}
Total (en equilibrio), por Bq de radón					34710	55.6	

- **Exposición:** se define como el producto del periodo de duración de la inhalación de descendientes de radón por su correspondiente concentración

Exposición de energía potencial alfa

$$P_p(T) = \int_0^T C_p(t)\, dt = \overline{C}_p\, T$$

J m^{-3} h // MeV m^{-3} h // WLM

Working Month (M) equivale a 170 horas trabajo al mes

1 WLM = 2.21· 10^{10} MeV m^{-3} h = 3.536·10^{-3} J m^{-3} h

Exposición equivalente en equilibrio

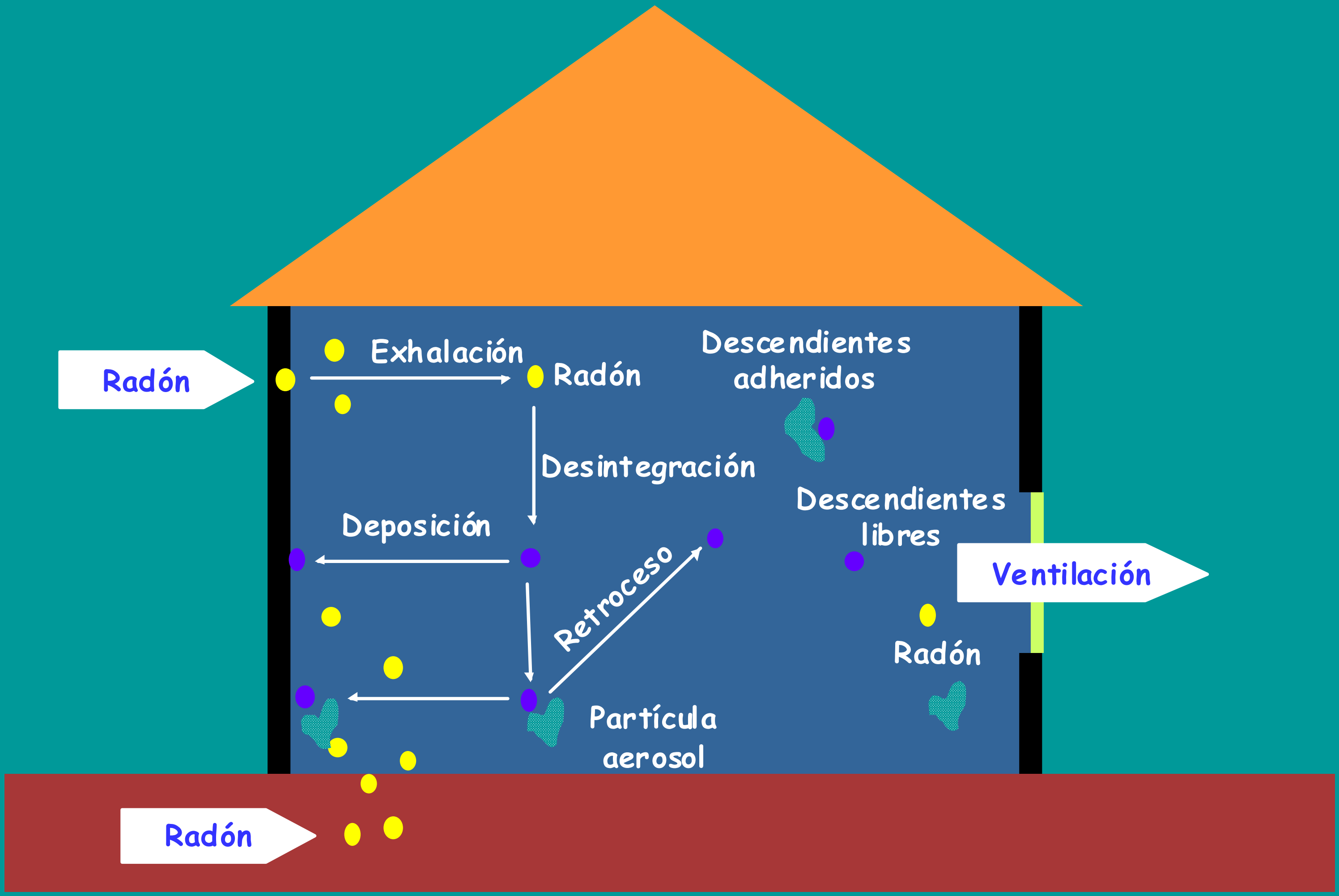
$$P_{eq}(T) = \int_0^T C_{eq}(t)\, dt = \overline{C}_{eq}\, T$$

Bq m^{-3} h

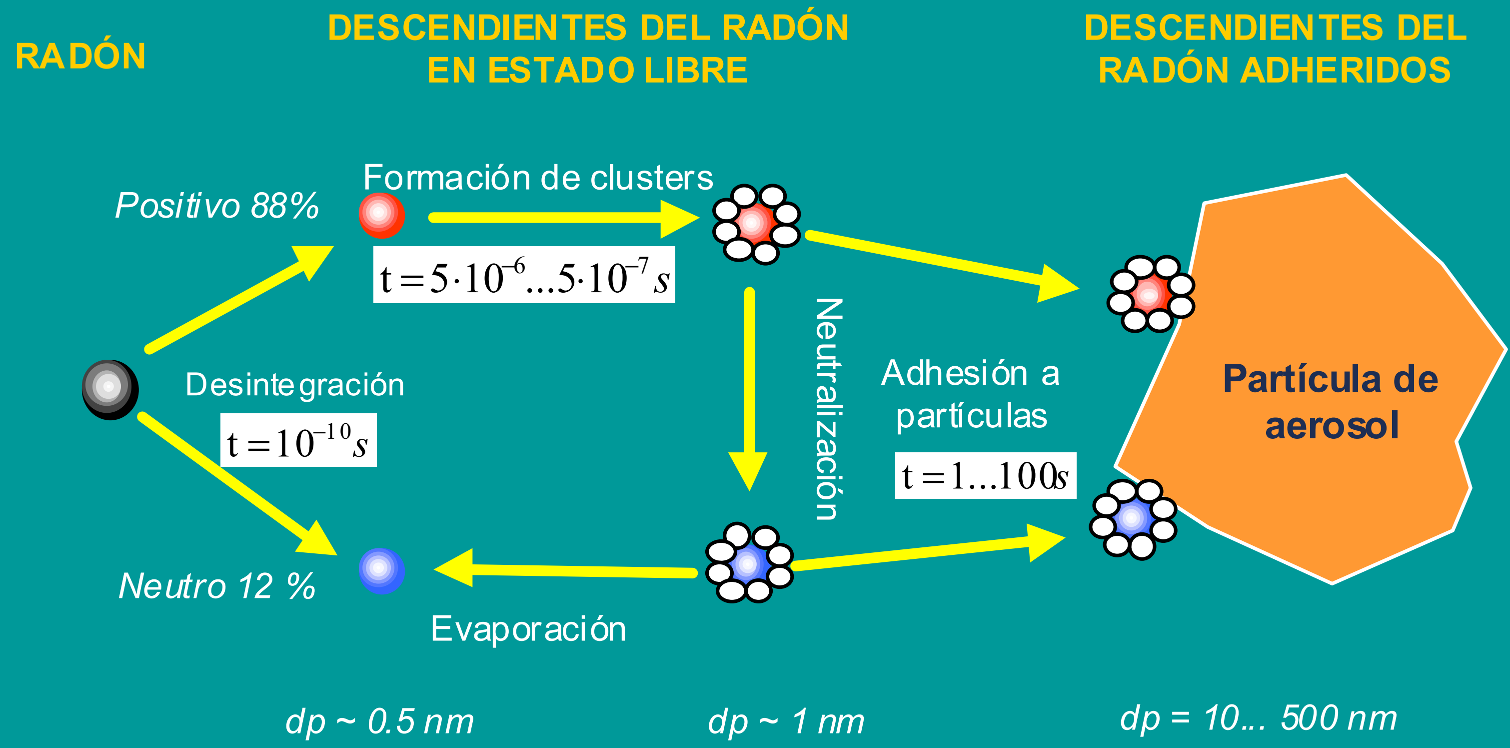
1 (Bq m^{-3} h)$_{Peq}$ = 1.57·10^{-6} WLM = 55.6·10^{-10} J m^{-3} h =

= 34710 MeV m^{-3} h

COMPORTAMIENTO DE LOS DESCENDIENTES DEL RADÓN EN EL INTERIOR DE UNA VIVIENDA



ESPECTRO DIMENSIONAL DE LOS DESCENDIENTES DEL RADÓN



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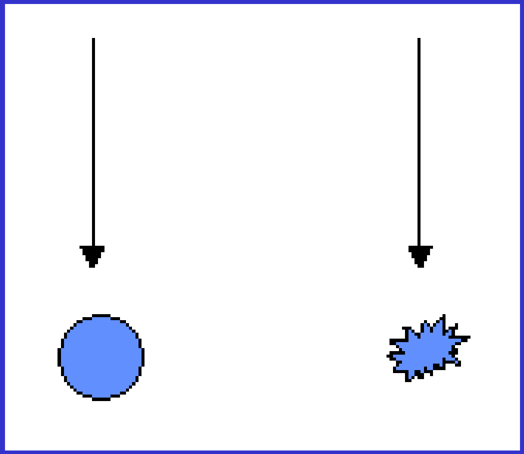
PARÁMETROS DE CARACTERÍZACIÓN DE UN RECINTO

- **Factor de equilibrio F y fracción libre f_p.**

$$F = \frac{C_{eq}}{C_{Rn-222}} \qquad f_p = \frac{C_{eq}^{f}}{C_{eq}}$$

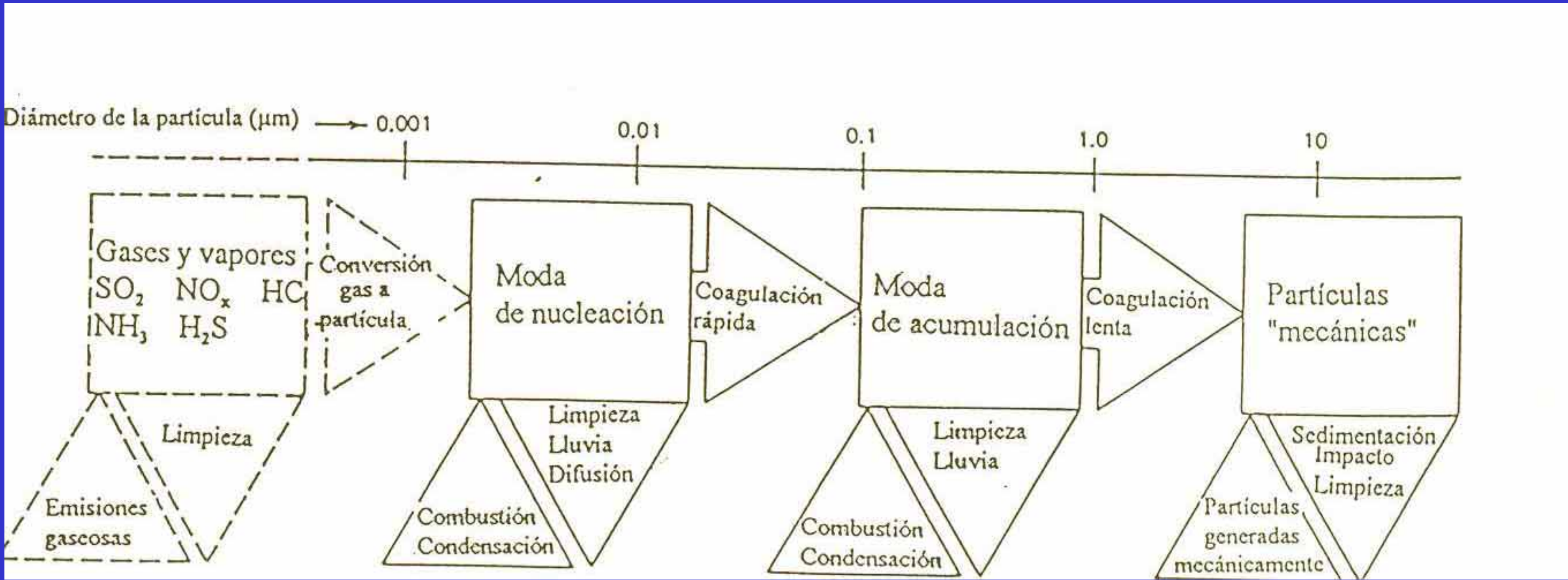
- **AMAD/AMTD** (activity median aerodinamic/thermodinamic diameter): diámetro aerodinámico/termodinámico mediano de la distribución del tamaño de partículas radiactivas adheridas/libres

esfera de diámetro 1 μm



Partícula de diámetro aerodinámico de 1 μm

AEROSOLES


Diámetro de la partícula (µm)
0.001
0.01
0.1
1.0
10
Gases y vapores
SO2 NOx HC
NH3 H2S
Conversión gas a partícula
Moda de nucleación
Coagulación rápida
Moda de acumulación
Coagulación lenta
Partículas "mecánicas"
Emisiones gaseosas
Limpieza
Combustión
Condensación
Limpieza
Lluvia
Difusión
Combustión
Condensación
Limpieza
Lluvia
Partículas generadas mecánicamente
Sedimentación
Impacto
Limpieza

ESTIMACIÓN DE LA DOSIS

$$E = \sum_i f_i \, E_i$$

mSv por WLM

mSv por Bq m^{-3} h

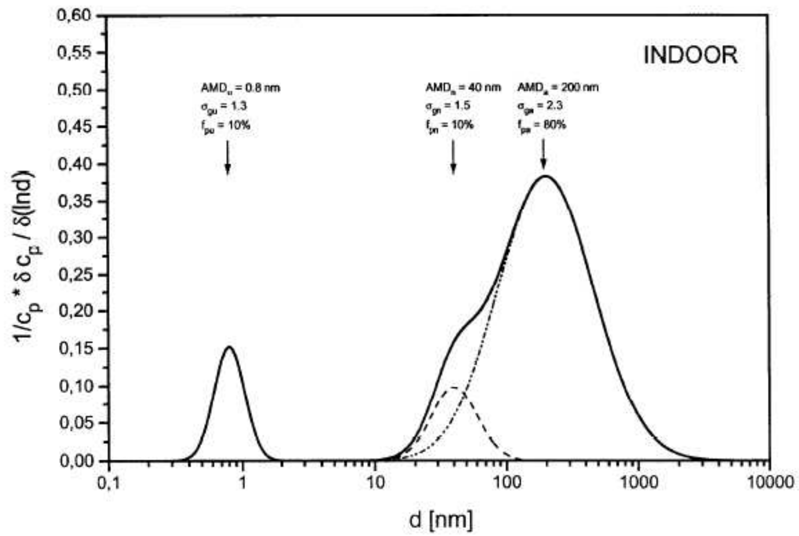


Fig. 3. Relative size distribution of the PAEC of radon daughters typical for indoor air in closed rooms of homes (without additional aerosol sources).

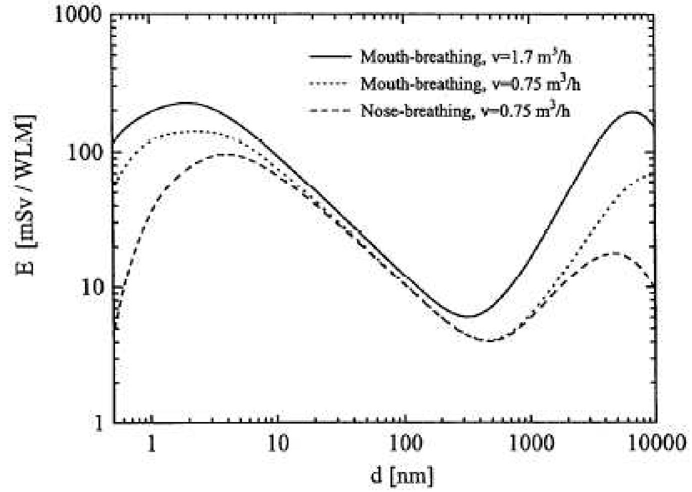
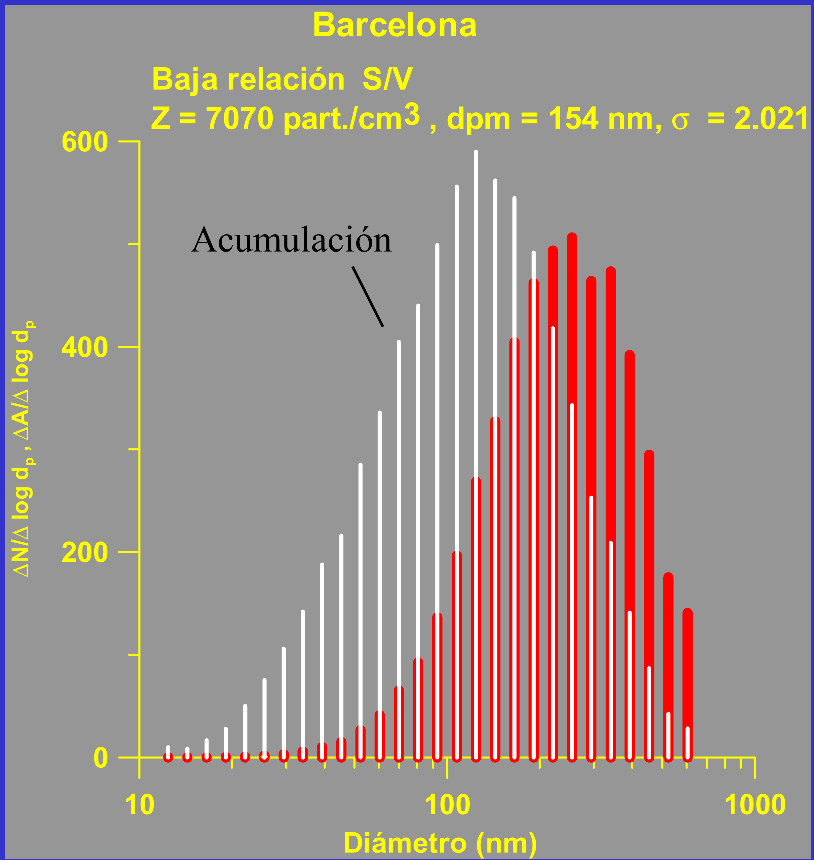
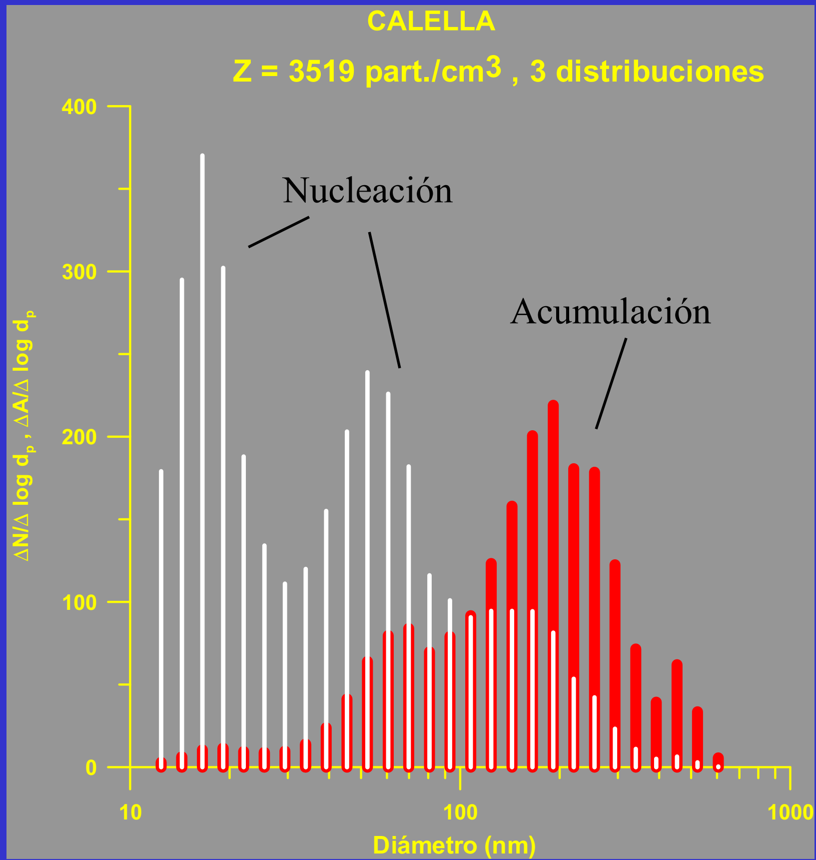


Fig. 2. DCF (in effective dose) as function of the particle diameter obtained from model calculations (Zock 1996) based on the human respiratory tract model of ICRP 66 (target tissue: secretory and basal cells; $w_R = 20$; $w_{TBB} : w_{Tbb} : w_{TAI} = 0.333 : 0.333 : 0.333$; $w_T = 0.12$).

(Porstendörfer 1996)

EJEMPLOS: ESPECTRO DIMENSIONAL DE PARTÍCULAS

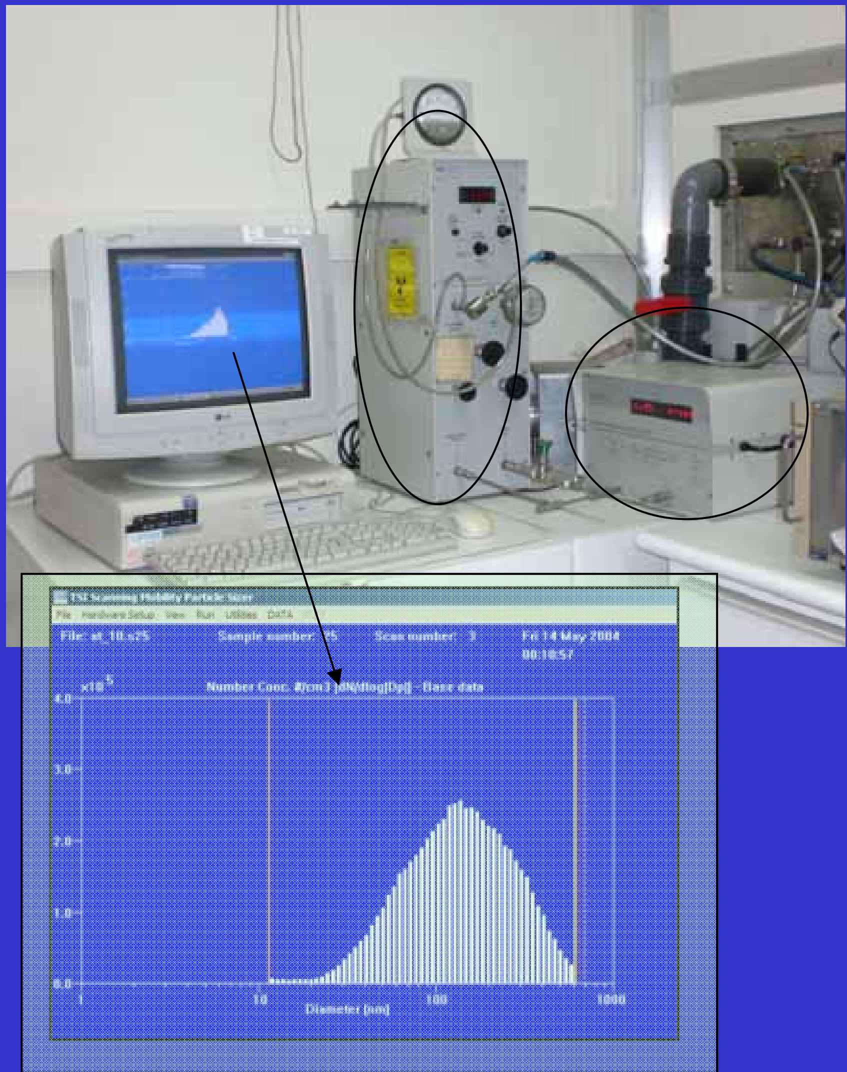


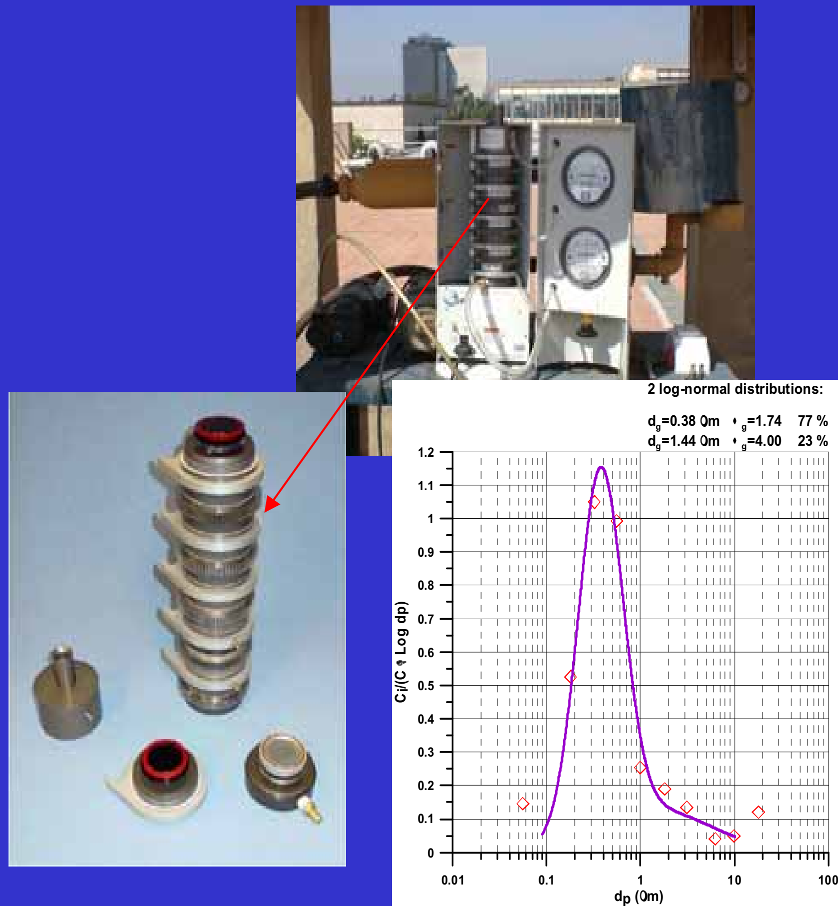


Distribución por tamaños del diámetro de partícula medido con un clasificador electrostático

Distribución por tamaños del diámetro de partículas radiactivas. Se estima mediante la aplicación del coeficiente de probabilidad de adhesión a la distribución medida con el clasificador electrostático

INSTRUMENTACIÓN ESPECTRO DIMENSIONAL





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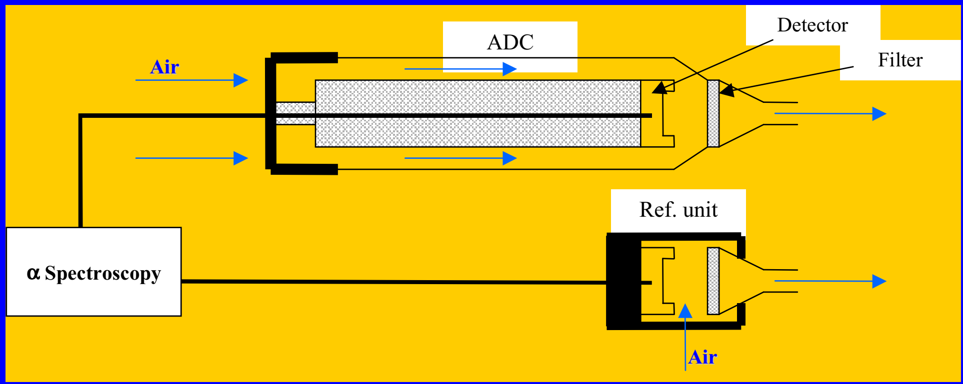
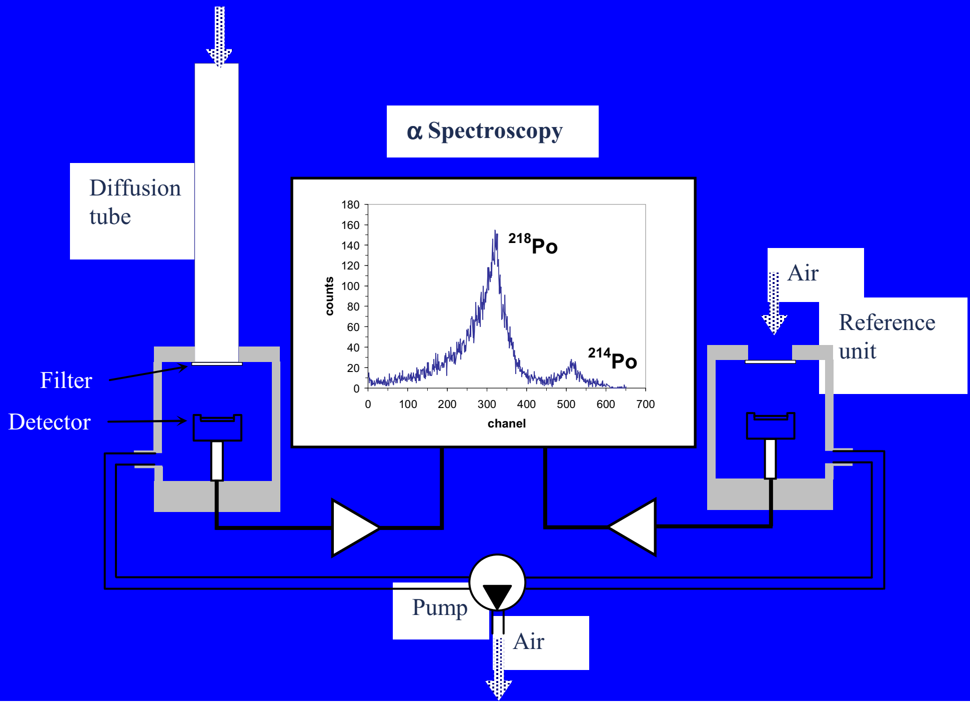
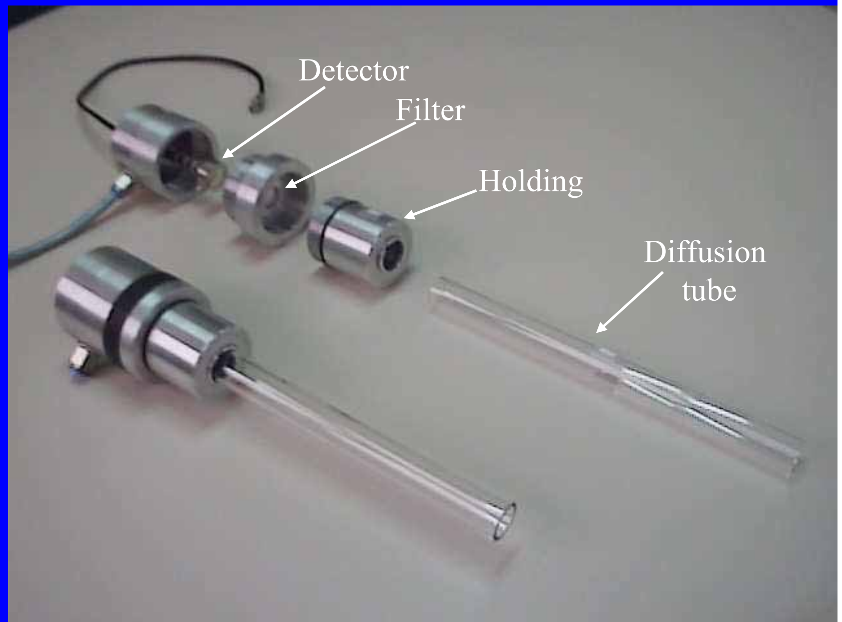
ANNULAR DIFFUSION CHANNEL (ADC) (IRSN-UBO)



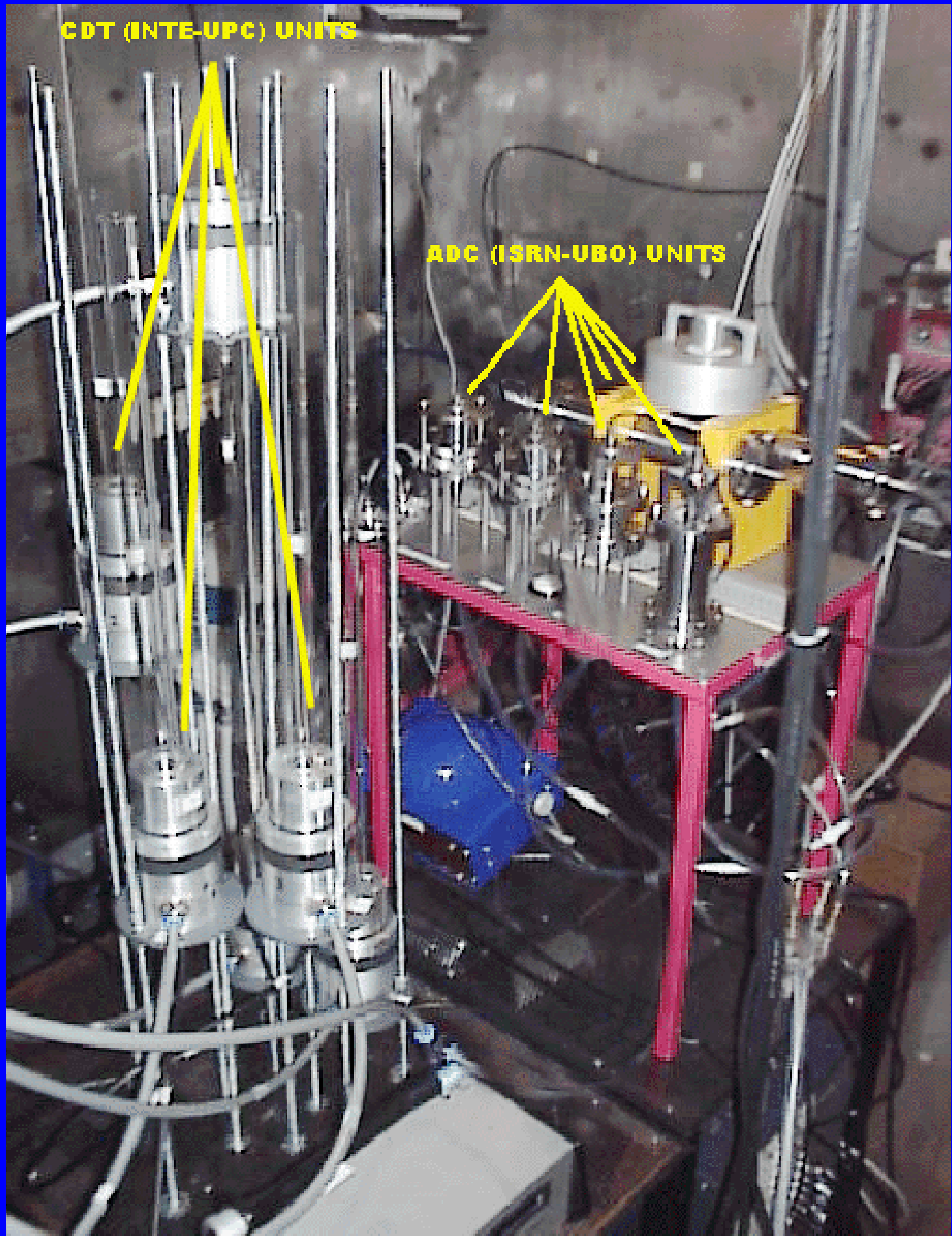
CYLINDRICAL DIFFUSION TUBE (CDT) (INTE-UPC)





RADON CHAMBER

Size	2.91×2.91×2.30 (20m^3)
Building material	2-mm-thick welded stainless steel sheets
^{222}Rn Exhalation	0-256 Bq·min^{-1} (2101 kBq ^{226}Ra source)
Ventilation	0-6 m^3·h^{-1}
Radon concentration	0-80000 Bq·m^3
Relative humidity	0-95 %
Temperature	5-50 ºC

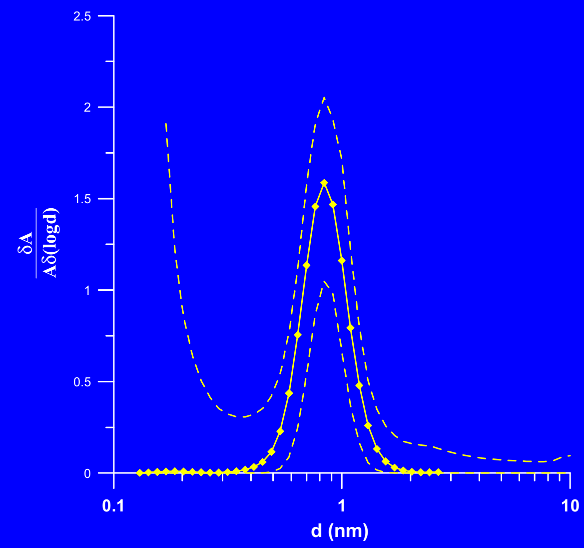


TAMAÑO más probable de unos 0.85 nm)

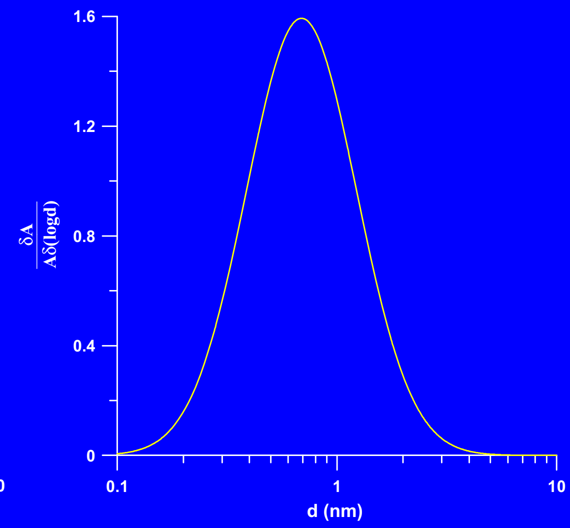
ADC

5.5 kBq m^{-3}

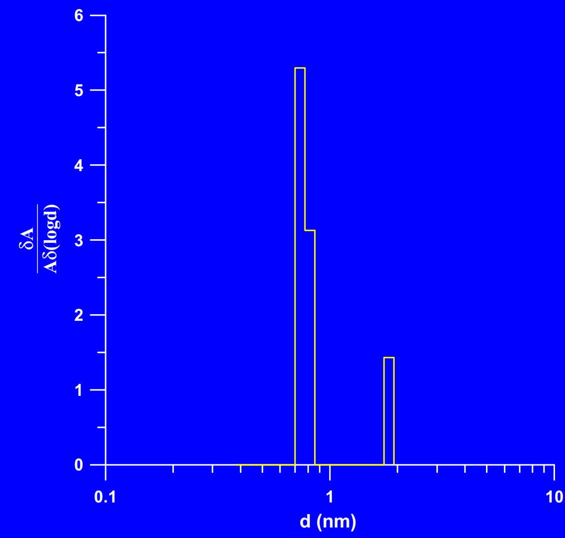
EVE



RW

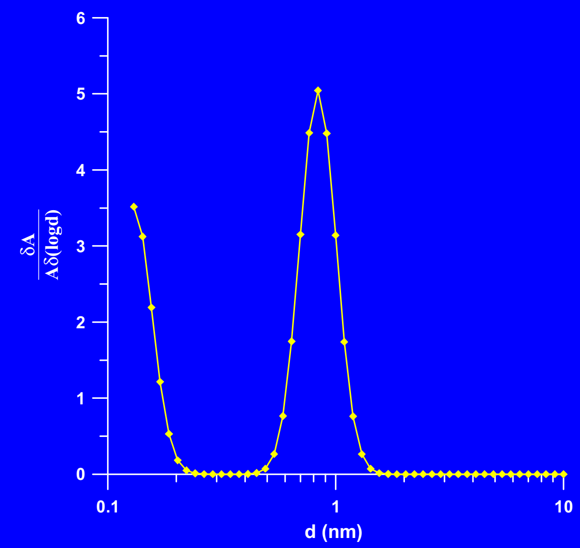


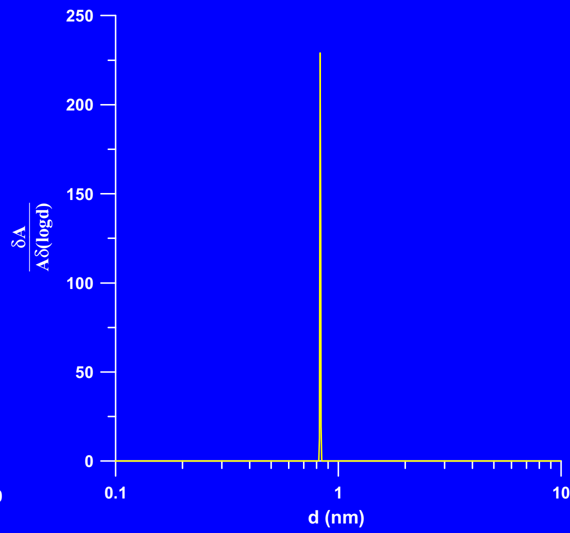
EMAX

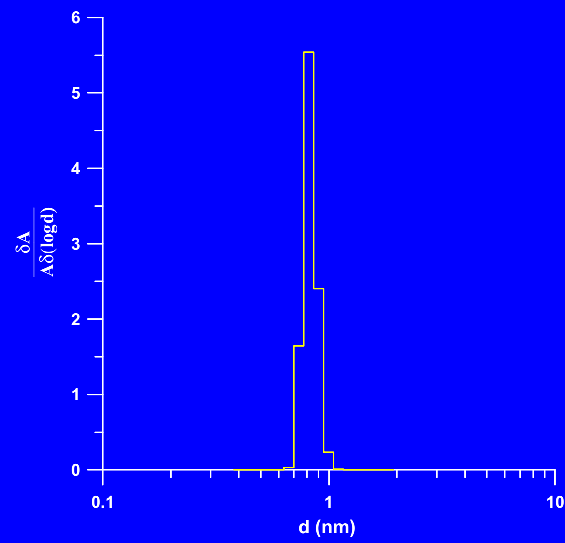


CDT

5.5 kBq m^{-3}







PARAMETROS DE ELEVADA SENSIBILIDAD A LA DOSIS

(Marsh and Birchall 2002)

Aerosoles
- Fracción libre, f_p
- Tamaño de la fracción libre
- Fracción de nucleación
- Tamaño de la fracción de nucleación

Persona
- Tasa de respiración
- Fracción respirada por la nariz/boca

Células
- Ubicación de las células (profundidad)
- Factores de ponderación asignados a los tejidos del pulmón (A_{BB}, A_{bb}, A_{AI})

Absorción en sangre → transferencia a otros órganos

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PARAMETROS DE ELEVADA SENSIBILIDD A LA DOSIS

Absorción en sangre → transferencia a otros órganos

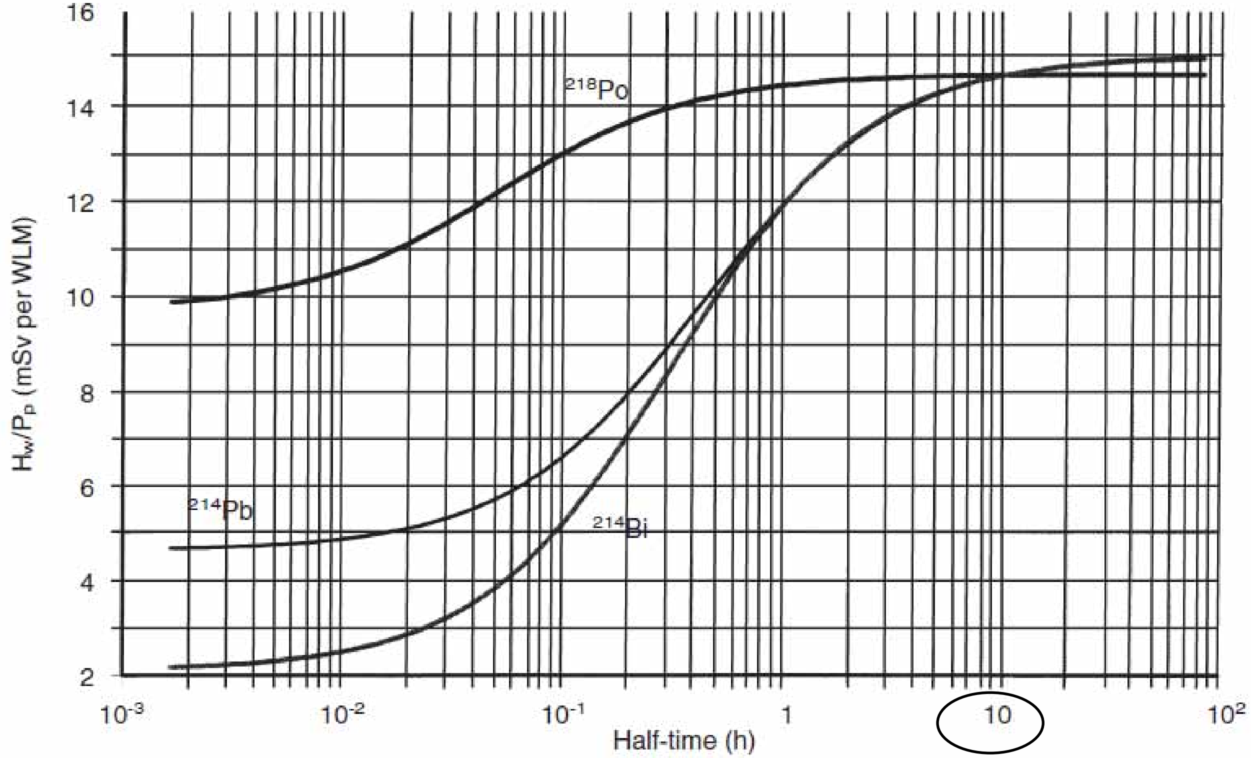


Figure 6. Sensitivity of weighted committed equivalent dose to lung per working level month (H_w/P_p) to the absorption half-times of ^{218}Po, ^{214}Pb or ^{214}Bi.

Valores representativos de los aerosoles para análisis con el modelo dosimétrico de la ICRP 66 en viviendas

Marsh et al.. Uncertainty analysis of the weighted equivalent lung dose per unit exposure to radon progeny in the home Rad. Prot. Dosim. 102(3), 229-248, 2002

Description of parameter	Representative value	Probability distribution		
		Form	a	b
Unattached fraction	0.1	Lognormal	0.11	2.3
Unattached aerosol size (AMTD)	0.8 nm	Lognormal	1.2 nm	2.1
Unattached dispersion	1.3	Uniform	1.0	1.4
Nucleation fraction	0.15	Right-angled triangle	0	0.5
Nucleation aerosol size (AMAD)	50 nm	Uniform	10 nm	90 nm
Nucleation dispersion	2.0	Uniform	1.0	3.0
Accumulation aerosol size (AMAD)	230 nm	Uniform	100 nm	360 nm
Accumulation dispersion	2.1	Lognormal	2.0	1.3
Coarse fraction	0.02	Right-angled triangle 1	0	0.2
Coarse aerosol size (AMAD)	2.5 µm	Uniform	1 µm	4 µm
Coarse dispersion	1.5	Uniform	1.4	2.5
Equilibrium factor	0.4	Normal	0.4	0.15

MODELO TRACTO RESPIRATORIO ICRP 66 SIMPLIFICADO APLICADO A LOS DESCENDIENTES DEL RADÓN

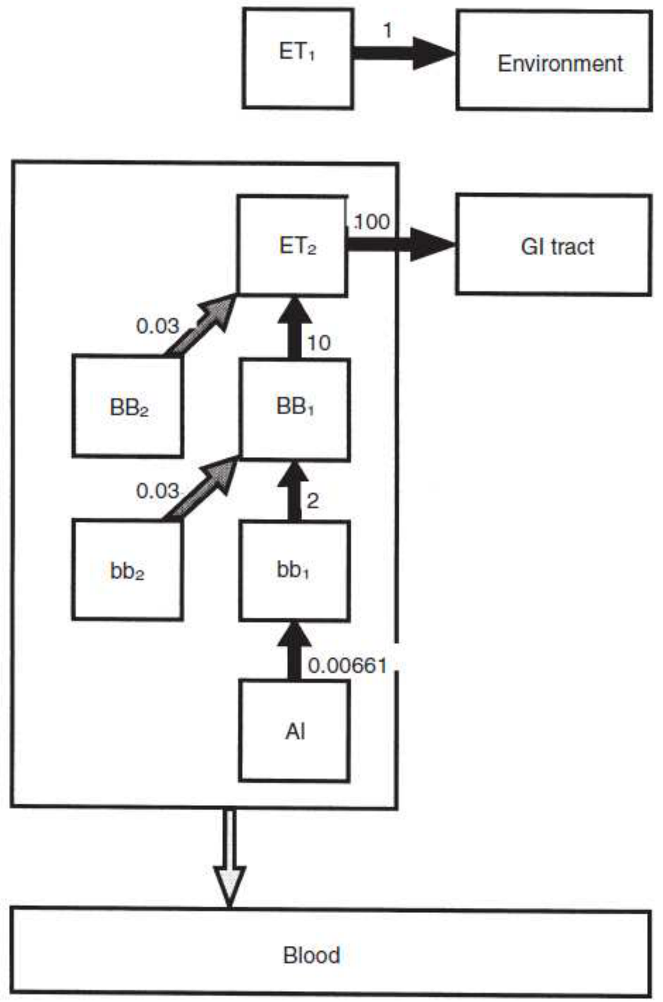
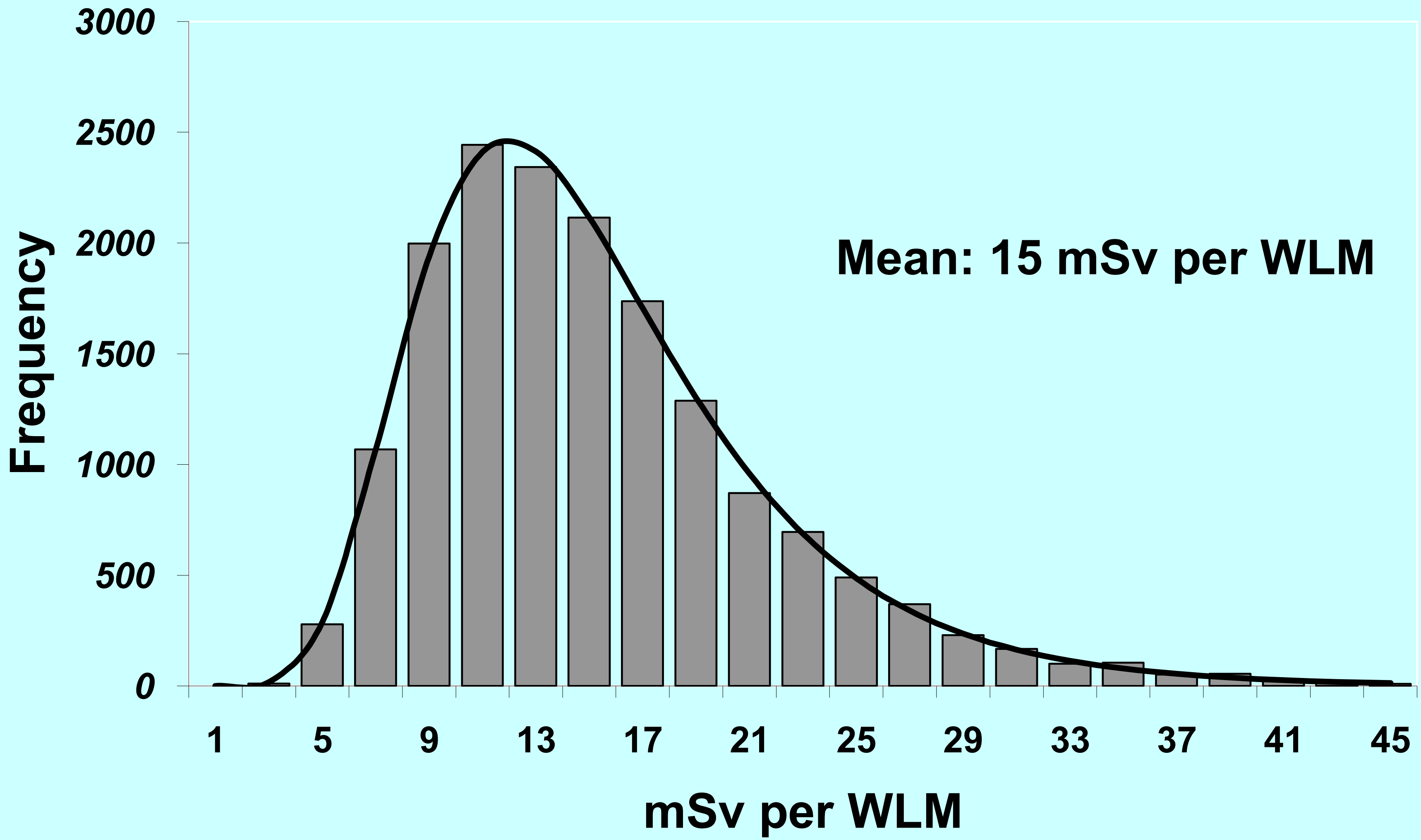
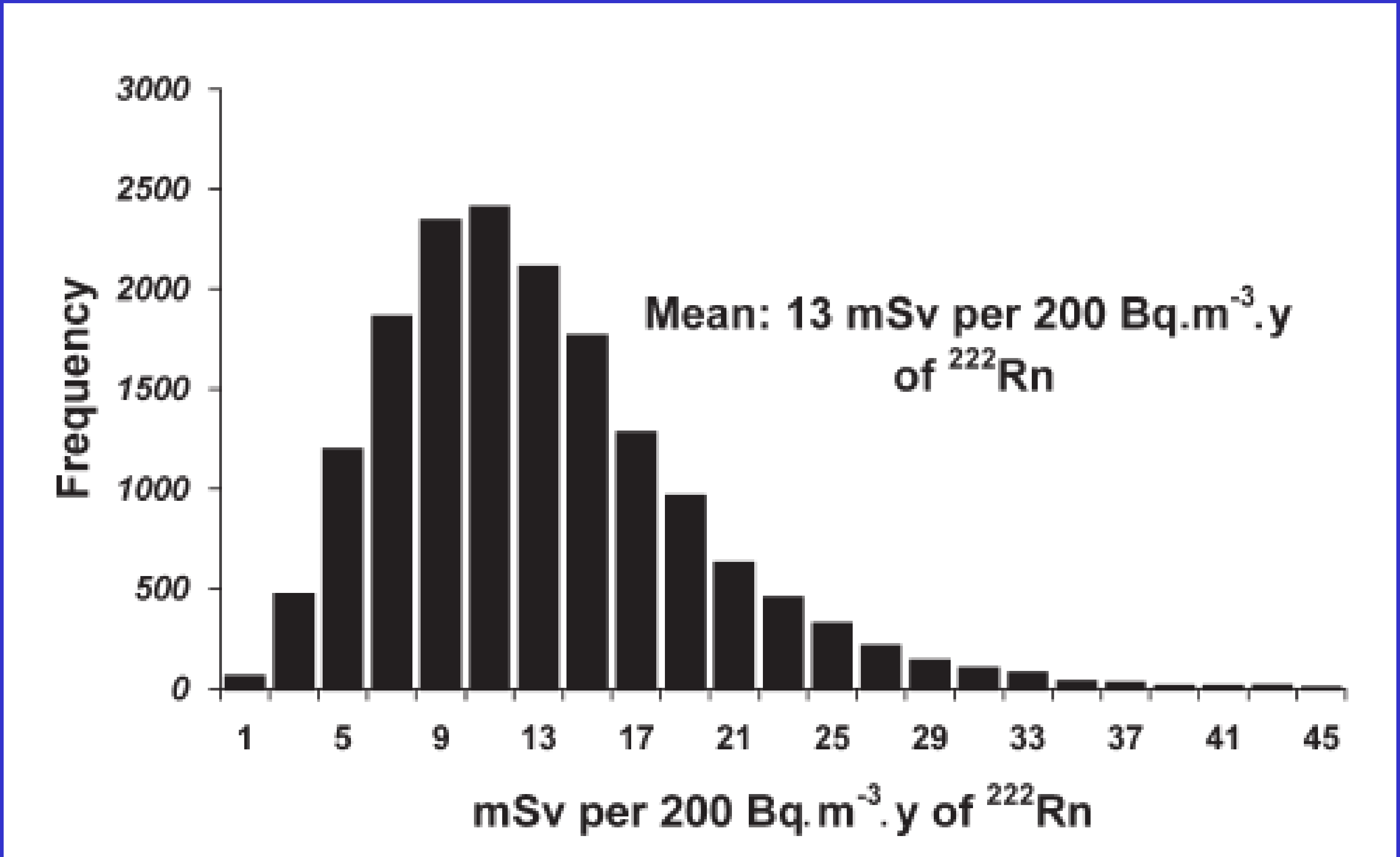


Figure 1. Simplified version of the HRTM. The rate constants given are in units of d^{-1}.

DISTRIBUCIÓN DE LA FRECUENCIA DE LA DOSIS EFECTIVA MODELO TRACTO RESPIRATORIO ICRP 66



DISTRIBUCIÓN DE LA FRECUENCIA DE LA DOSIS EFECTIVA MODELO TRACTO RESPIRATORIO ICRP 66



ESTIMACIÓN DE LA DOSIS EFECTIVA POR UNIDAD DE EXPOSICIÓN

- Estimación mediante estudios dosimétricos (ICRP 66)

miembros del público (f_p=0.1)

$$E / P_P = 11.3 + 43\ f_p \approx 15\ \ mSv\ por\ WLM$$

Como $1\ Bq\ m^{-3}\ h)_{eq} = 1.57 \cdot 10^{-6}\ WLM$

$E/P_{eq} = 23\ nSv\ por\ (Bq\ m^{-3}\ h)_{Peq}$

- Estimación por unidad de exposición a radón (miembros del público)

Para F=0.4
y f_p = 0.1

$$E = 1.57\ F(11.3 + 43\ f_p)\ \approx 9.5\ \ nSv\ por\ (Bq\, m^{-3}\ h)_{radon}$$

CARACTERÍSTICAS LUGARES DE MEDIDA

Alcover: 400 Bq m^{-3}. Low V/S
Old Farmhouse. Material: stone

Cardedeu: 300 Bq m^{-3}
Detached house. Material: brick

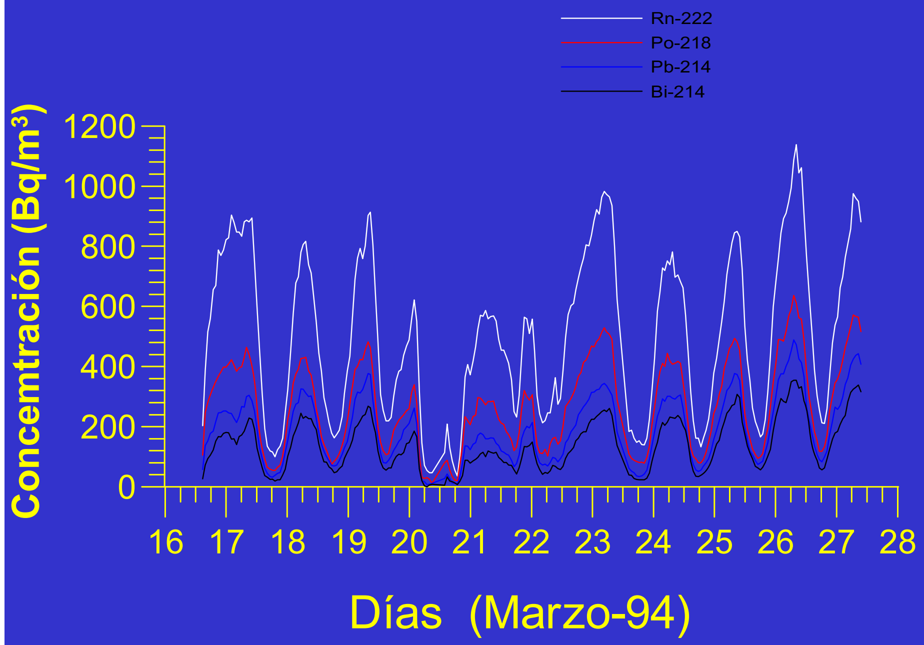
Calella: 450 Bq m^{-3}
Three-story house on a small hill 100m.
Material: brick

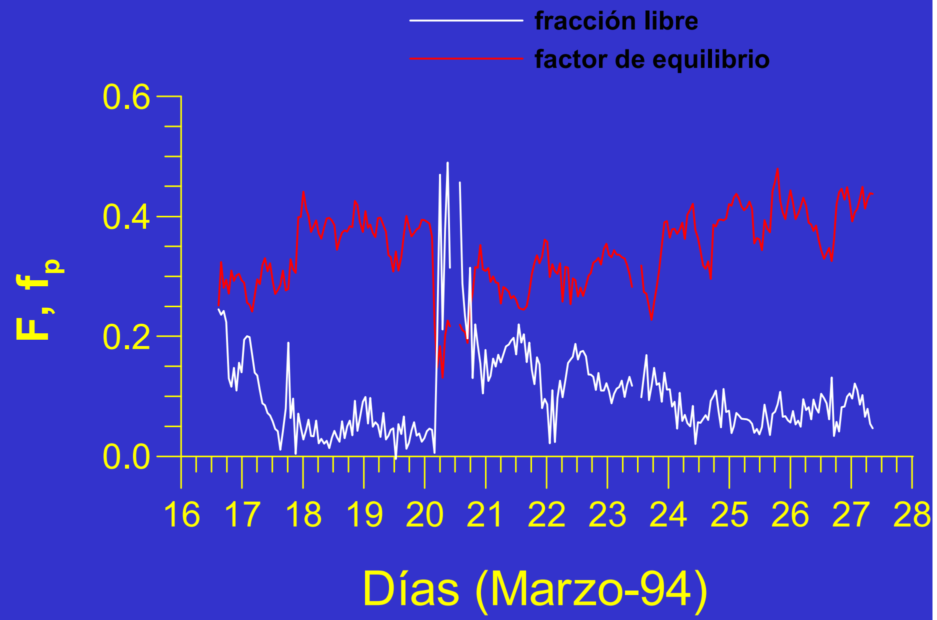
Barcelona: 200 Bq m^{-3}. High V/S
Decommissioned training reactor.
Material: 35-cm concrete

Resumen resultados

Site	$C_{Rn\text{-}222}$ (Bq m^{-3})	F ([a] arithmetic mean/deviation) ([g] geometric mean/deviation)	f_p ([a] arithmetic mean/deviation) ([g] geometric mean/deviation)	Z (part. cm^{-3})
Cardedeu	**200 (100 – 500)**	**0.17[a] ⌖ 0.03**	**0.23[g] ⌖ 1.40**	**$1.6\ 10^3$**
Alcover	**400 (100 – 1000)**	**0.06[g] ⌖ 1.43**	**0.43[a] ⌖ 0.15**	**($4\ 10^2 – 10^4$)**
Barcelona	**200 (100 – 300)**	**0.73[g] ⌖ 1.09**	**0.03[a] ⌖ 0.02**	**$7.3\ 10^3$**
Calella	**450 (10 – 3000)**	**0.39[a] ⌖ 0.10**	**0.13[g] ⌖ 1.49**	**($1.3\ 10^3 – 4.7\ 10^3$)**

FLUCTUACIONES DIARIAS EN CALELLA





EQUIPOS DE MEDIDA DESCENDIENTES

DOSEman-PRO

EQF-3020

WLx

E-RPSIU

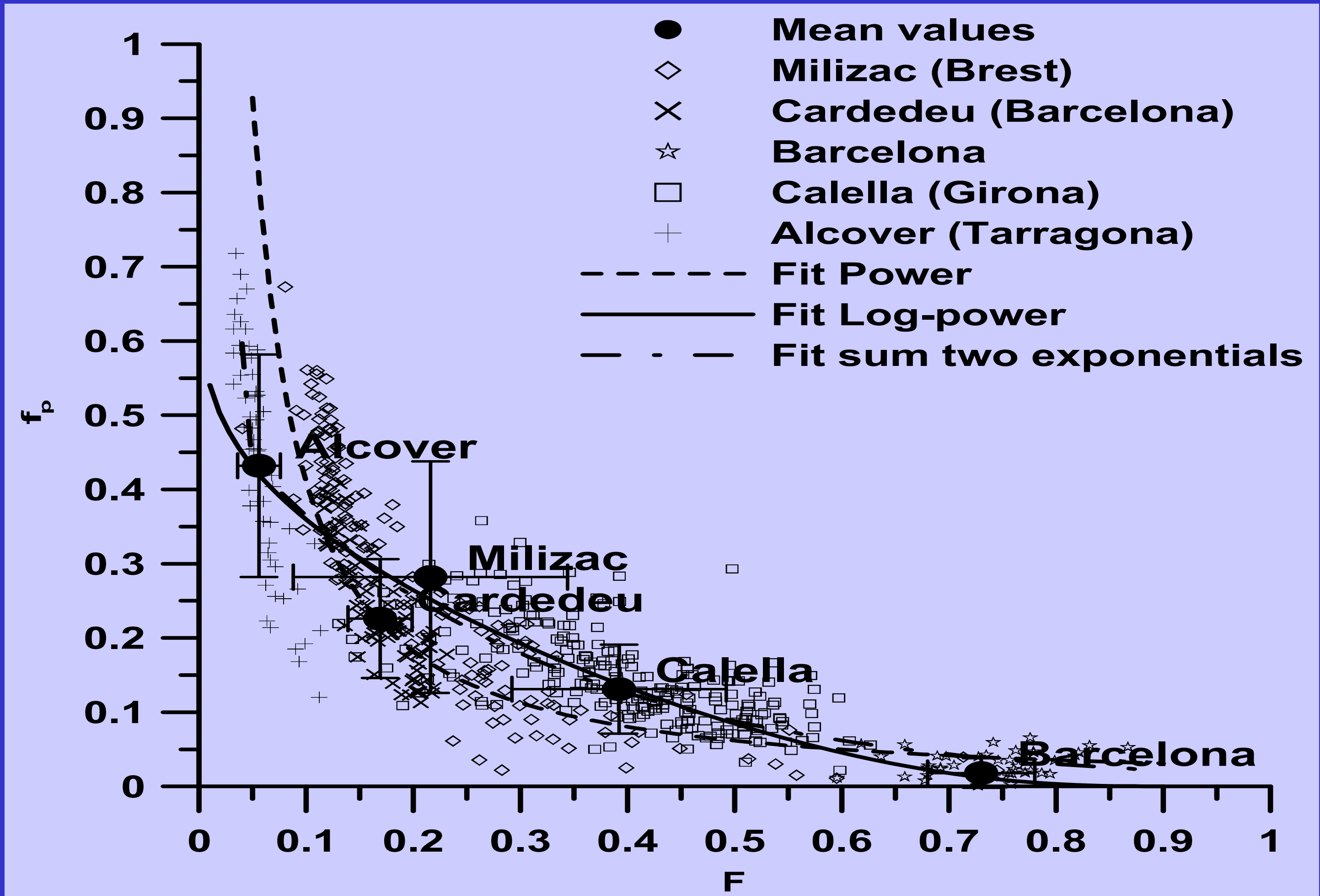
TN-WL-2

CORRELACIÓN ENTRE F Y f_P

Potencial $fp=0.0273\ F^{-1.177}$

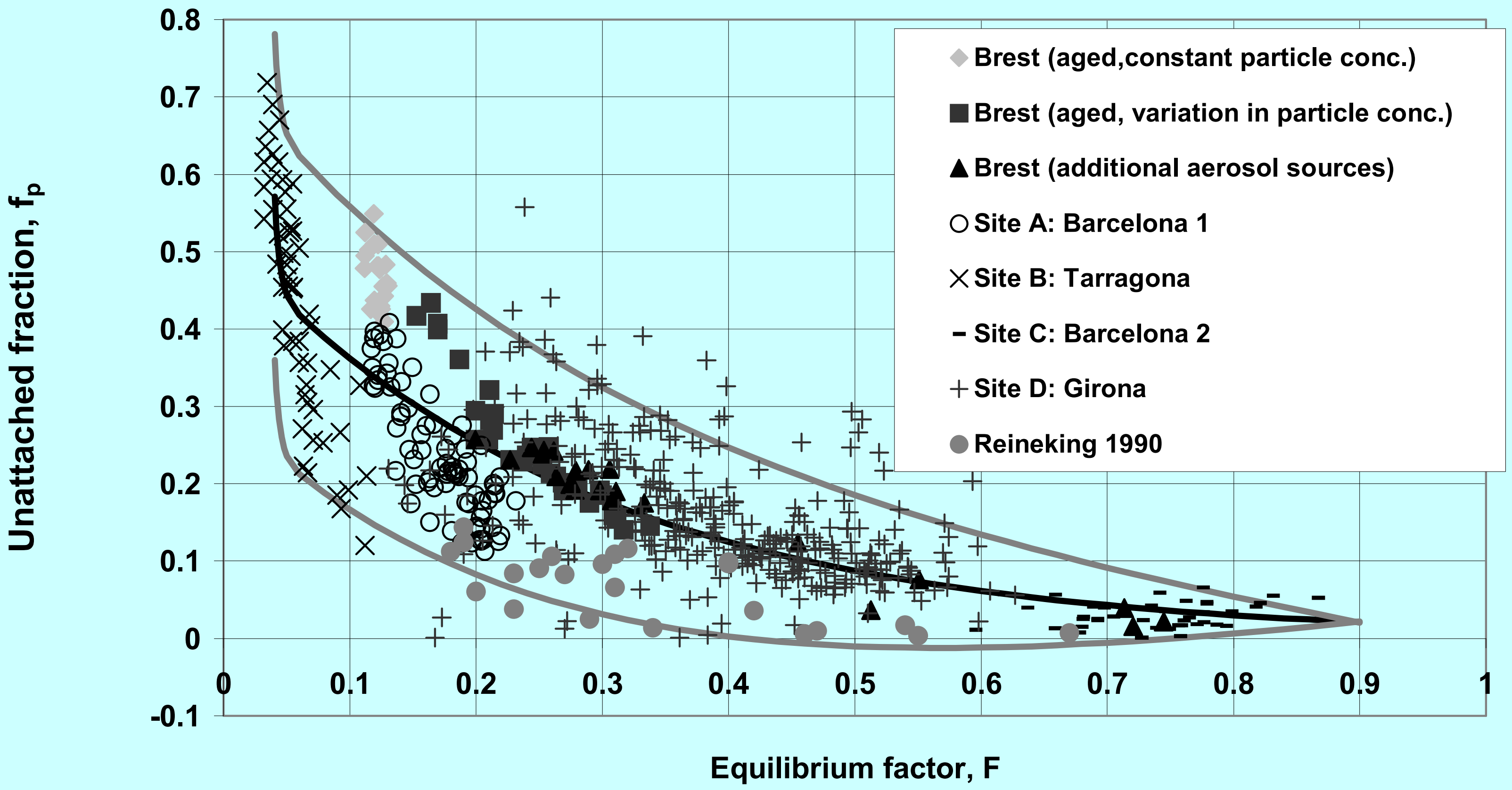
Log-potencial $\ln(1/fp)=1.888\ [\ln(1/F)]^{-0.735}$

Suma de dos exponenciales $fp = 25.6\ e^{-136\ F} + 0.54\ e^{-3.79\ F}$



CORRELACIÓN ENTRE F Y f_P

Marsh et al.. Uncertainty analysis of the weighted equivalent lung dose per unit exposure to radon progeny in the home Rad. Prot. Dosim. 102(3), 229-248, 2002



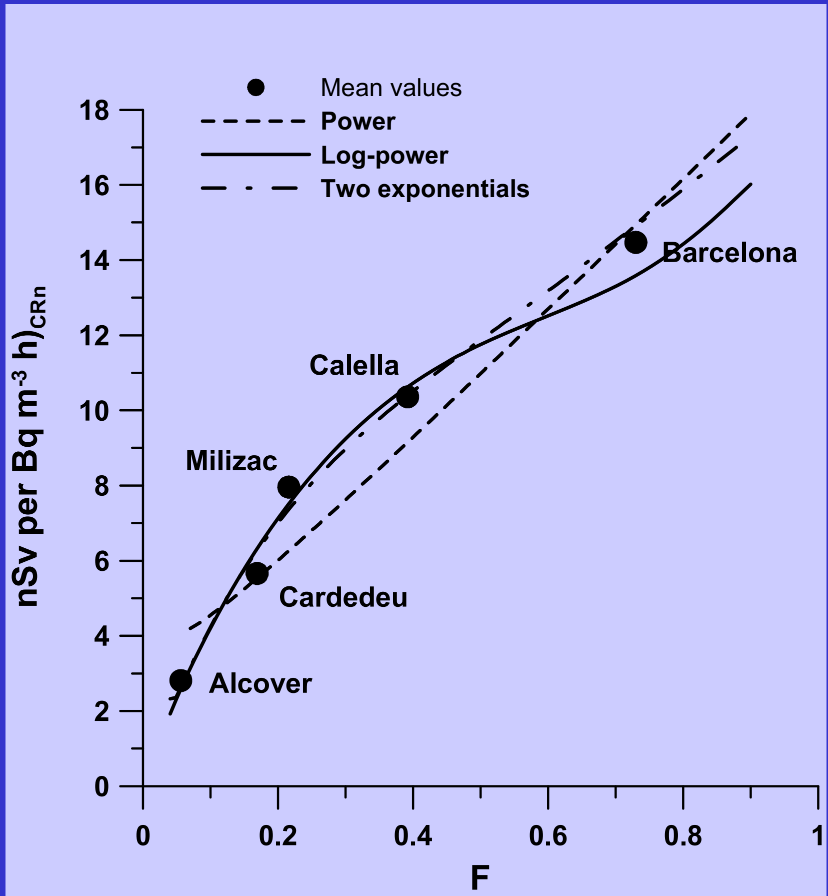
CORRELACIÓN ENTRE F Y f_P

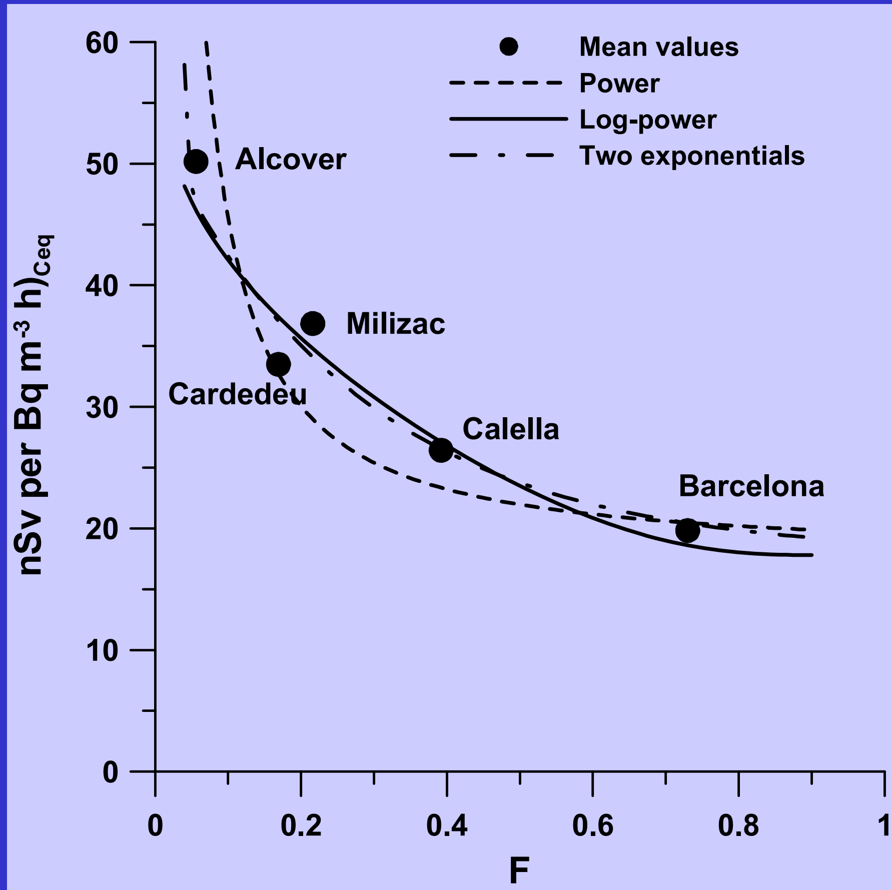
$E = F\,(67.5\ fp + 17.8)$

nSv per Bq m^{-3} $h)_{radón}$

$E = 67.5\ fp + 17.8$

nSv per (Bq m^{-3} $h)_{Ceq}$





CORRELACIÓN ENTRE Z Y f_P

Huet 2001

Particle concentration, unattached fraction of PAEC, unattached fraction of radon daughters and equilibrium factor under different aerosol conditions

	Z $\times 10^3$ part/cm^3	fp	f_{Po}	f_{Pb}	f_{Bi}	F
Aged	1.2 (0.5–5)	0.31 (0.67–0.08)	0.69 (0.86–0.37)	0.23 (0–0.61)	0.08 (0–0.37)	0.16 (0.04–0.45)
Cooking	250 (80–600)	0.046 (0.01–0.09)	0.18 (0.03–0.3)	0.017 (0–0.09)	0 (0–0.02)	0.27 (0.15–0.4)
Fumigating sticks	100 (60–450)	0.02 (0.01–0.05)	0.069 (0.047–0.17)	0.017 (0–0.075)	0	0.49 (0.3–0.59)
Candles	390 (100–1000)	0.032 (0.022–0.047)	0.10 (0.01–0.16)	0.023 (0.014–0.06)	0	0.31 (0.26–0.35)
Cigar	80 (60–300)	0.024 (0.012–0.039)	0.10 (0.07–0.15)	0.001 (0–0.007)	0.001 (0–0.007)	0.56 (0.26–0.74)

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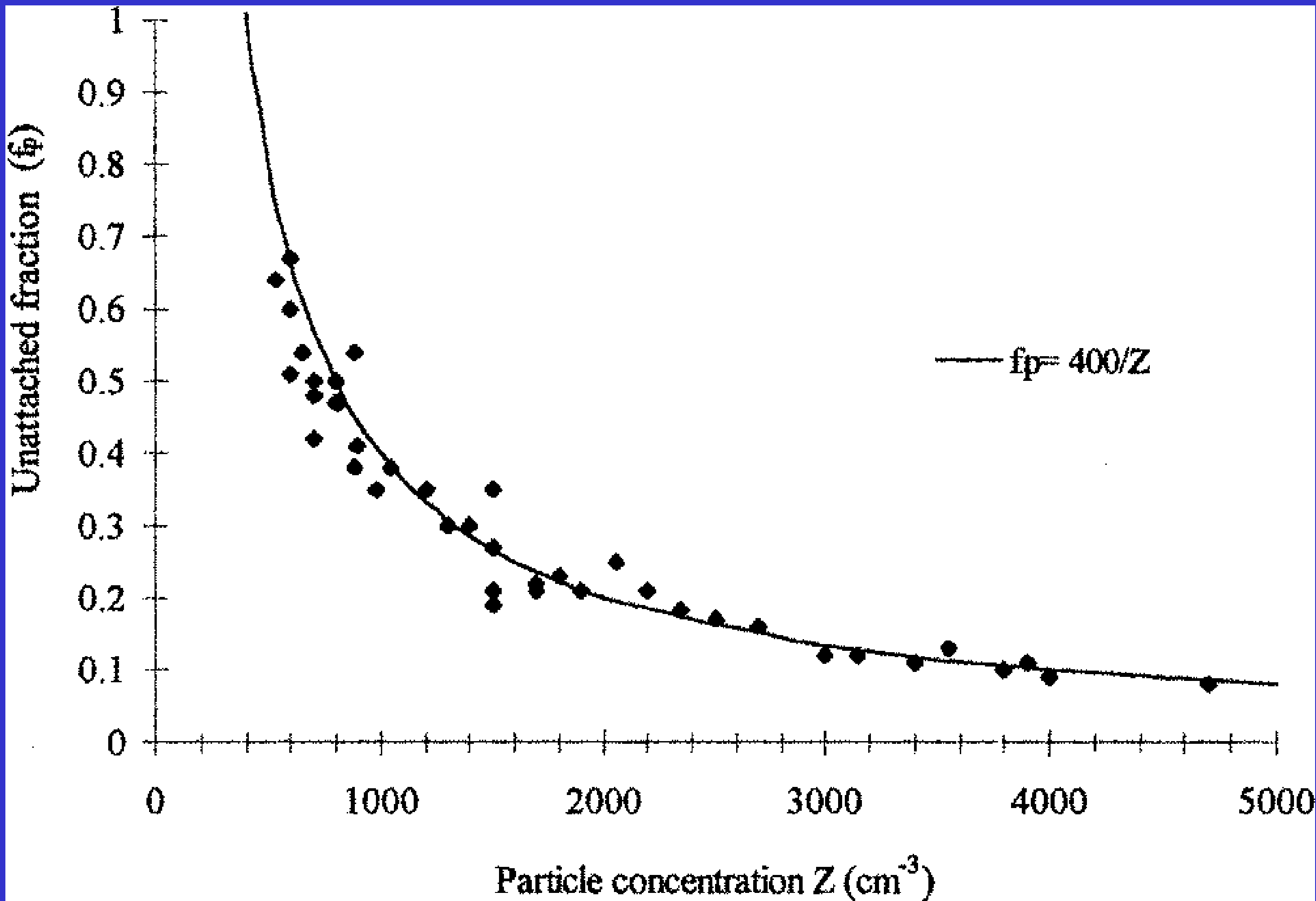
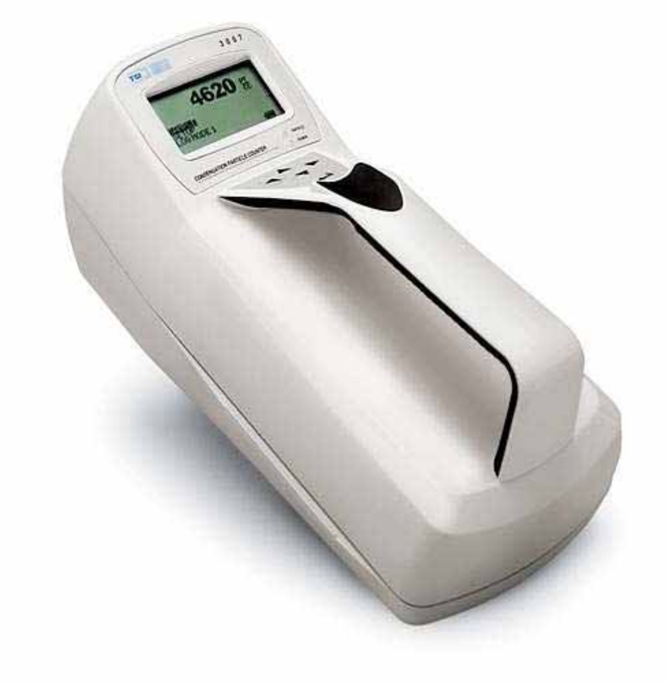
CORRELACIÓN ENTRE Z Y f_P

$$fp = 400 / Z$$



CORRELACIÓN ENTRE Z Y f_P

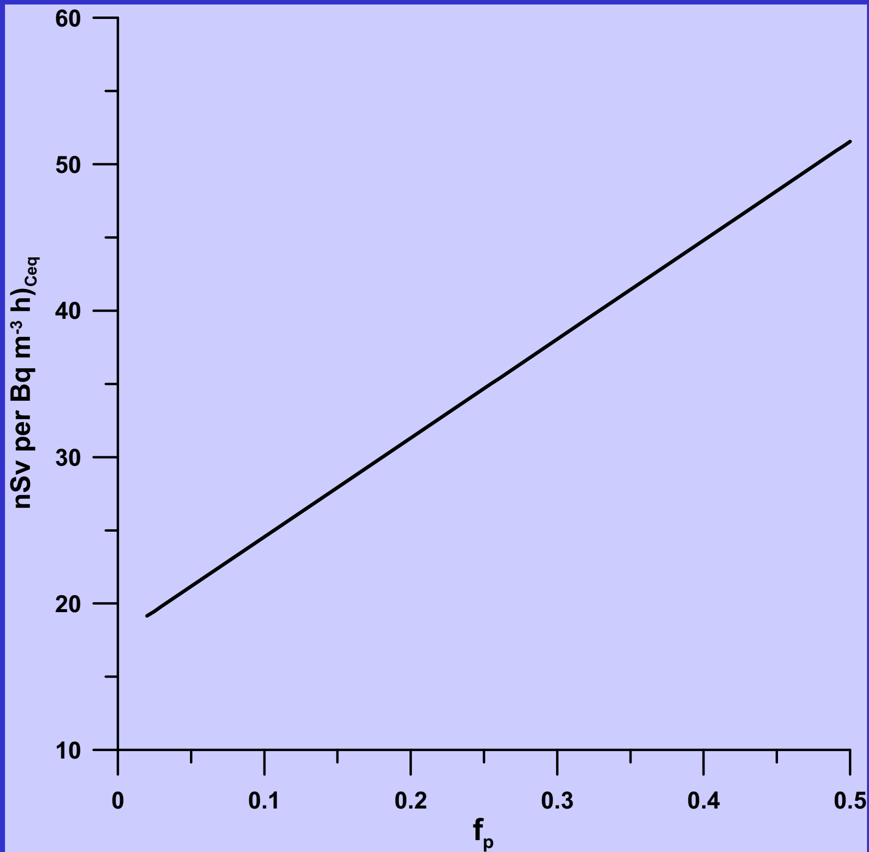


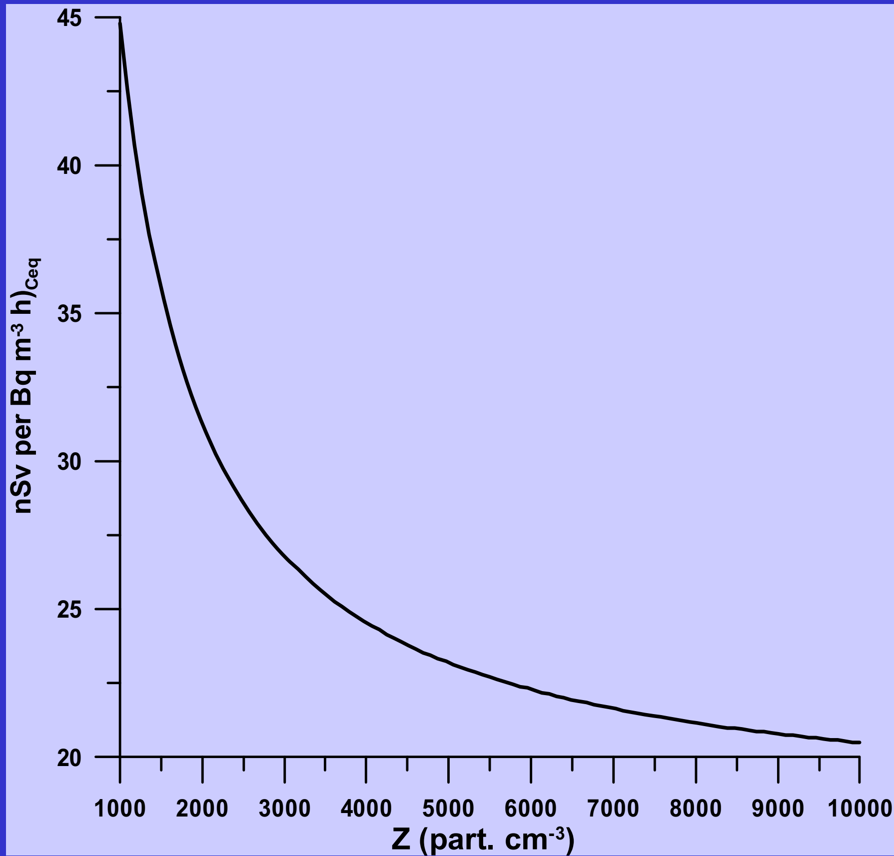
CORRELACIÓN ENTRE Z Y f_P

$E = 67.5\ fp + 17.8$ nSv per $(Bq\ m^{-3}\ h)_{Ceq}$

$E = 27000\ /Z + 17.8$ nSv per $(Bq\ m^{-3}\ h)_{Ceq}$

$fp = 400\ /Z$





RESUMEN

Sólo se conoce la exposición en Concentración de Radón

$E = F\,(67.5\,fp + 17.8)$ nSv per Bq m^{-3} h)$_{radón}$

Sólo se conoce la exposición en Concentración de energía potencial alfa (PAEC)

$E = 43\,fp + 11.3$ mSv per WLM

$E = 67.5\,fp + 17.8$ nSv per (Bq m^{-3} h)$_{Ceq}$

Además se conoce la concentración de partículas (Z)

$E = 17200/Z + 11.3$ mSv per WLM

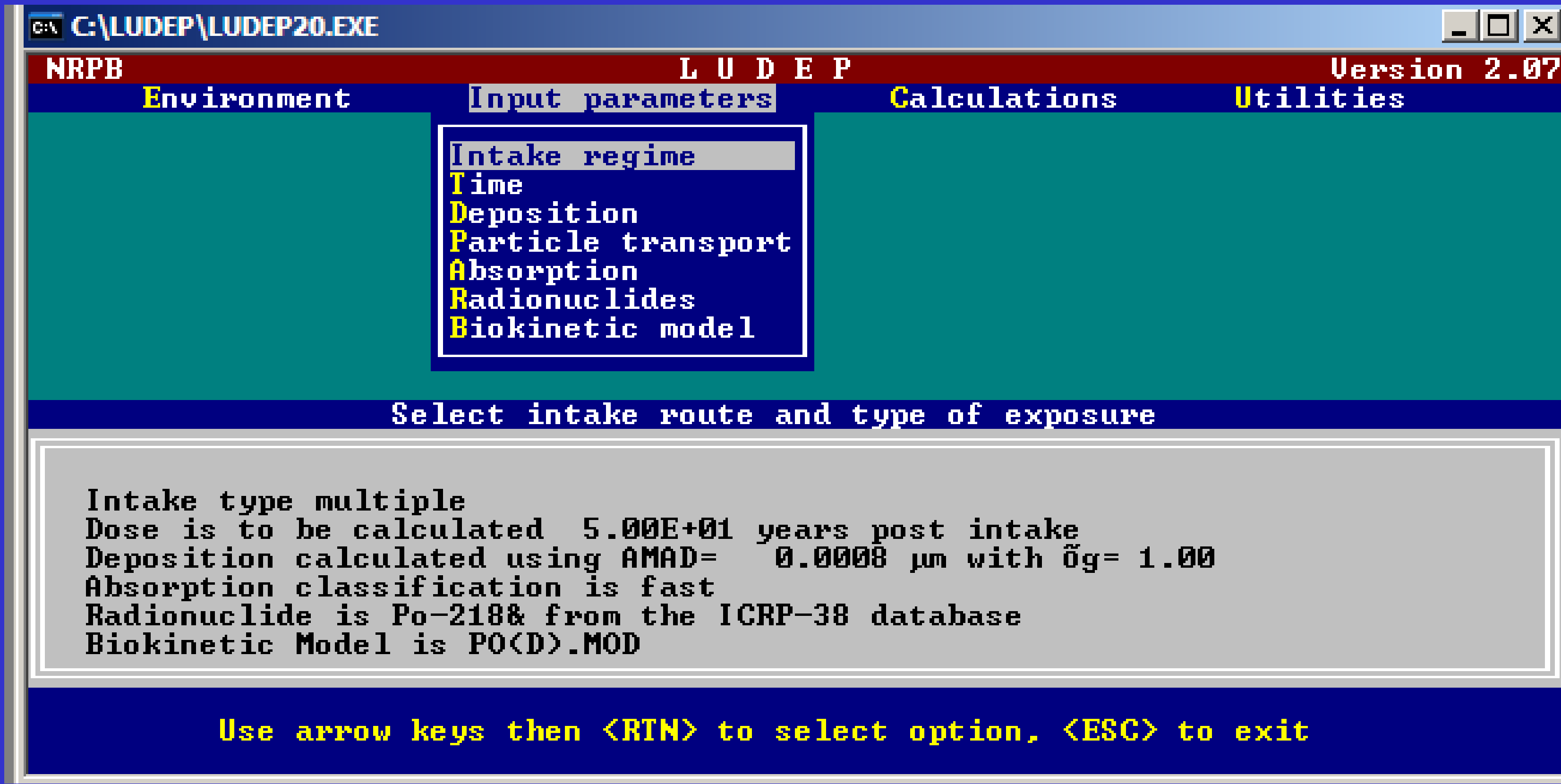
$E = 27000/Z + 17.8$ nSv per (Bq m^{-3} h)$_{Ceq}$

Además se conoce el tamaño de los aerosoles y sus fracciones

$$E = \sum_i f_i\, E_i$$

mSv per WLM Tablas, gráficas o código

LUDEP


C:\LUDEP\LUDEP20.EXE
NRPB
L U D E P
Version 2.07
Environment
Input parameters
Calculations
Utilities
Intake regime
Time
Deposition
Particle transport
Absorption
Radionuclides
Biokinetic model
Select intake route and type of exposure
Intake type multiple
Dose is to be calculated 5.00E+01 years post intake
Deposition calculated using AMAD= 0.0008 µm with õg= 1.00
Absorption classification is fast
Radionuclide is Po-218& from the ICRP-38 database
Biokinetic Model is PO(D).MOD
Use arrow keys then <RTN> to select option, <ESC> to exit

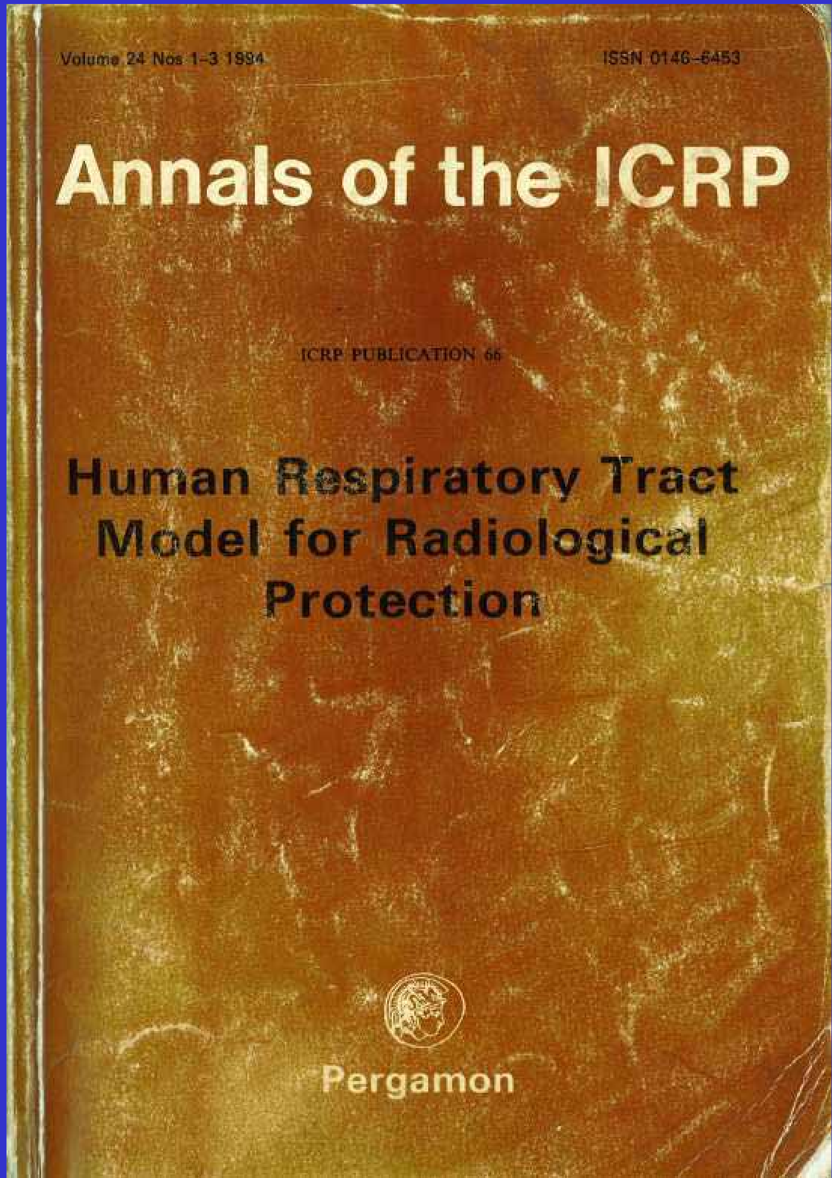
LUDEP

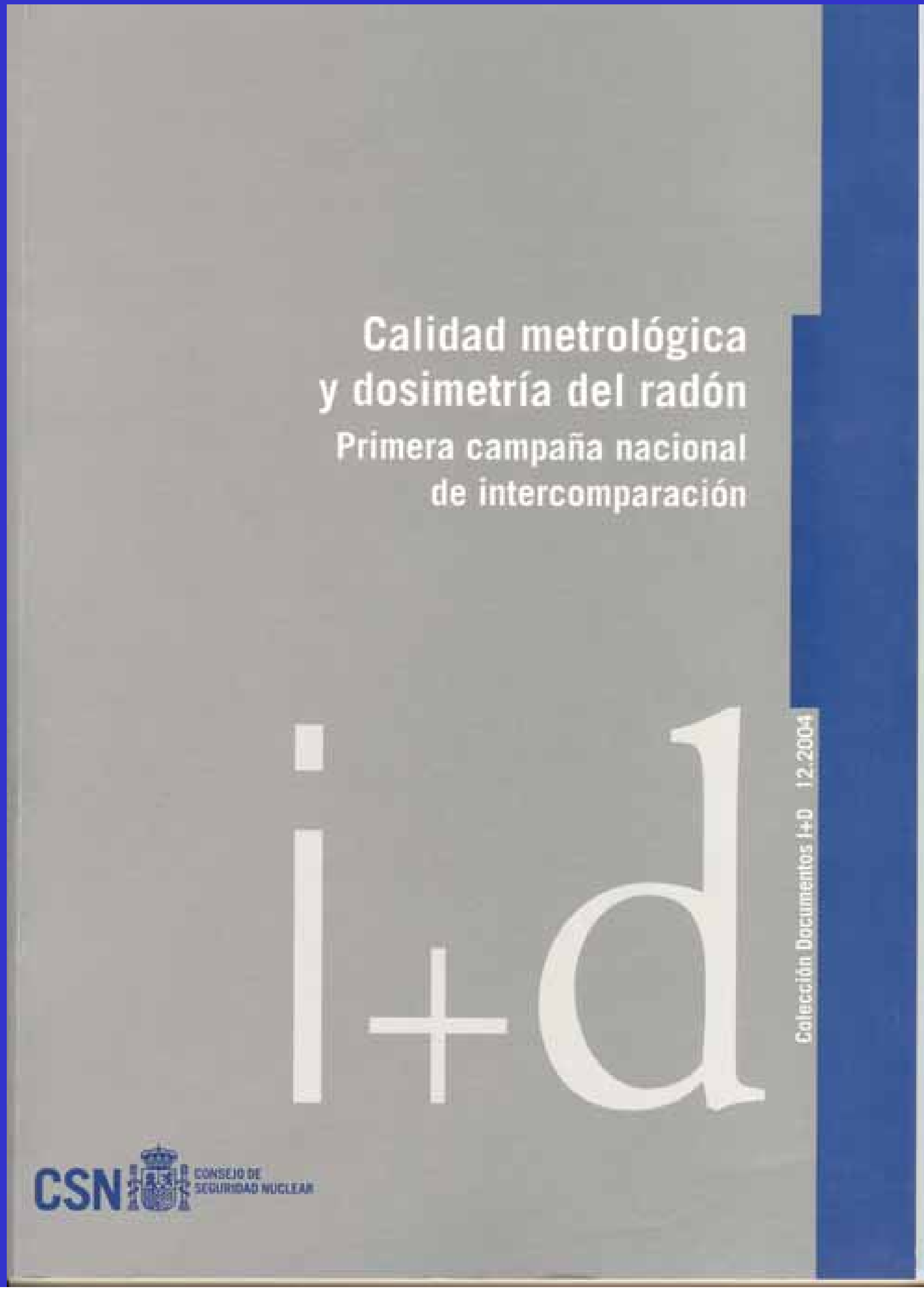
Organ	Equivalent Dose	WT	Weighted Equiv Dose
Breasts	1.683E-11 Sv	0.050	8.413E-13 Sv
Stomach wall	1.895E-11 Sv	0.120	2.274E-12 Sv
Liver	1.725E-11 Sv	0.050	8.623E-13 Sv
Lungs	2.974E-08 Sv	0.120	3.568E-09 Sv
Gonads	1.669E-11 Sv	0.200	3.337E-12 Sv
Bone marrow	1.732E-11 Sv	0.120	2.079E-12 Sv
Bone surfaces	9.129E-12 Sv	0.010	9.129E-14 Sv
Skin	1.670E-11 Sv	0.010	1.670E-13 Sv
Thyroid	1.675E-11 Sv	0.050	8.373E-13 Sv
Urinary bl wall	1.668E-11 Sv	0.050	8.339E-13 Sv
Colon	1.669E-11 Sv	0.120	2.003E-12 Sv
Oesophagus	1.687E-11 Sv	0.050	8.435E-13 Sv

The maximum organ dose is 2.974E-08 Sv to the Lungs
which is a named organ, therefore

Remainder	2.159E-11 Sv	0.050	1.079E-12 Sv

Effective Dose is 3.584E-09 Sv


Volume 24 Nos 1-3 1994
ISSN 0146-6453
Annals of the ICRP
ICRP PUBLICATION 66
Human Respiratory Tract
Model for Radiological
Protection
Pergamon


Calidad metrológica
y dosimetría del radón
Primera campaña nacional
de intercomparación
i+d
Colección Documentos I+D 12.2004
CSN
CONSEJO DE
SEGURIDAD NUCLEAR

Radiation Protection Dosimetry
Vol. 87, No. 3, pp. 167–178 (2000)
Nuclear Technology Publishing

SENSITIVITY ANALYSIS OF THE WEIGHTED EQUIVALENT LUNG DOSE PER UNIT EXPOSURE FROM RADON PROGENY

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National Radiological Protection Board
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Received August 25 1999, accepted October 25 1999

Abstract — A sensitivity analysis has been performed to identify those ICRP Publication 66 Human Respiratory Tract Model parameters which significantly affect the lung dose arising from the inhalation of radon progeny under conditions found in houses. The analysis was performed to investigate the sensitivity of the weighted committed equivalent dose to lung per unit radon progeny exposure to (i) aerosol parameters, (ii) subject related parameters, (iii) target cell parameters, and (iv) the absorption rates of radon progeny. The weighted committed equivalent dose per unit exposure to radon progeny varied between 8 mSv and 33 mSv per working level month for conditions of radon progeny in homes. The parameters most affecting the equivalent lung dose are identified. The analysis also showed that the absorption rates of the radon progeny would have to be substantially faster than the current estimates (ln 2/10 h^{-1}) to have an effect on the equivalent lung dose.

Pergamon

Environment International, Vol. 22, Suppl. 1, pp. S563–S583, 1996

0160-4120/96 $15.00+.00

PII S0160-4120(96)00158-4

RADON: MEASUREMENTS RELATED TO DOSE*

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EI 9510-352 M (Received 29 October 1995; accepted 17 June 1996)

In the first part of the paper, the parameters of the airborne radon daughters for dose estimation are defined. In the second part, the most important methods and techniques for measurement of the potential alpha energy concentration, the unattached fraction (cluster-fraction), and the activity size distribution of the radon decay products are reported. At the end, the dose conversion factor for different exposure situations obtained from model calculations are presented. These values vary between 6 mSv/WLM and 39 mSv/WLM depending on aerosol condition and Physiological parameters of inhalation (inhalation rate, nose/mouth breathing) at different places (home, open air, working places). These factors are based on the new human respiratory tract model of ICRP 66, taking into account the different radon daughter characteristics.

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Radon dosimetry and its implication for risk

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National Radiological Protection Board, Didcot, Oxon, UK

Abstract. The major source of human exposure to radiation is from natural background, and the largest component of this arises from the inhalation of the short-lived daughters of radon gas (^{222}Rn). It is therefore important to be able to quantify the risk from this exposure. The risk from exposure to radon daughters can be determined in two different ways. Firstly, by using statistics on the excess lung cancer incidence in miners exposed to high levels of radon gas: the so-called *epidemiological* approach. Secondly, by calculating the effective dose (Sv) received per unit exposure, and multiplying this by the risk per Sv: the so-called *dosimetric* approach. When, in 1994, the ICRP Publication 66 Human Respiratory Tract Model (HRTM) was first used in the latter approach, the estimates of risk (8.4×10^{-4}/WLM) exceeded those of the epidemiological approach (2.8×10^{-4}/WLM) by a factor of 3. Since then, there have been many attempts to reconcile these two approaches, bearing in mind that if any of the ICRP weighting factors (e.g. tissue or radiation weighting factors) were changed by a factor of 3, to make these two approaches agree, this would have a significant effect on the dosimetry of other radionuclides, and may not be justified by other experimental evidence. This paper re-examines these two approaches, and the likely uncertainties associated with each, in the light of recent scientific knowledge. Recent risk estimates using the epidemiological approach ($\sim5\times10^{-4}$/WLM) are nearly twice those made in 1994, while a recent detailed analysis using the dosimetric approach gives a risk about 15% lower than the 1994 study ($\sim7\times10^{-4}$/WLM). Based on these current estimates, the two approaches are broadly consistent. It is observed that a small change in the weighting factor for the lung, from 0.12 (rounded by ICRP from 0.11) to 0.10 is all that is needed to make these two approaches agree almost exactly.

Keywords: Radon; Exposure; Risk; Dosimetry; Epidemiology

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Radiation Protection Dosimetry
Vol. 102, No. 3, pp. 229–248 (2002)
Nuclear Technology Publishing

UNCERTAINTY ANALYSIS OF THE WEIGHTED EQUIVALENT LUNG DOSE PER UNIT EXPOSURE TO RADON PROGENY IN THE HOME

J. W. Marsh†, A. Birchall†, G. Butterweck‡, M.-D. Dorrian†, C. Huet§, X. Ortega‖, A. Reineking*, G. Tymen§, Ch. Schuler‡, A. Vargas‖, G. Vezzu‡ and J. Wendt*
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‖Universitat Politècnica de Catalunya, Institut de Tecniques Energetiques
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Received November 1 2001, revised March 23 2002, accepted April 23 2002

Abstract — A parameter uncertainty analysis has been performed to derive the probability distribution of the weighted equivalent dose to lung for an adult (w_{lung} H_{lung}) per unit exposure to radon progeny in the home. The analysis was performed using the ICRP Publication 66 human respiratory tract model (HRTM) with tissue weighting factor for the lung, $w_{lung} = 0.12$ and the radiation weighting factor for alpha particles, $w_R = 20$. It is assumed that the HRTM is a realistic representation of the physical and biological processes, and that the parameter values are uncertain. The parameter probability distributions used in the analysis were based on a combination of experimental results and expert judgement from several prominent European scientists. The assignment of the probability distributions describing the uncertainty in the values of the assigned fractions (A_{BB}, A_{bb}, A_{AI}) of the tissue weighting factor proved difficult in practice due to lack of quantitative data. Because of this several distributions were considered. The results of the analysis give a mean value of w_{lung} H_{lung} per unit exposure to radon progeny in the home of 15 mSv per working level month (WLM) for a population. For a given radon gas concentration, the mean value of w_{lung} H_{lung} per unit exposure is 13 mSv per 200 Bq.m^{-3}.y of ^{222}Rn. Parameters characterising the distributions of w_{lung} H_{lung} per unit exposure are given. If the ICRP weighting factors are fixed at their default values (A_{BB}, A_{bb}, A_{AI} = 0.333, 0.333, 0.333; $w_{lung} = 0.12$; and $w_r = 20$) then on the basis of this uncertainty analysis it is extremely unlikely ($P \approx 0.0007$) that a value of H_w/P_p for exposure in the home is as low as 4 mSv per WLM, the value determined with the epidemiological approach. Even when the uncertainties in the A_{BB}, A_{bb}, A_{AI} values are included then this probability is predicted to be between 0.01 to 0.08 depending upon the distribution assumed for describing the uncertainties in the A_{BB}, A_{bb}, A_{AI} values. Thus, it is concluded that the uncertainties in the HRTM parameters considered in this study cannot totally account for the discrepancy between the dosimetric and epidemiological approaches.

ANALYSIS OF THE DOSE CONVERSION FACTOR PER UNIT EXPOSURE TO RADON AND RADON PROGENY USING THE ICRP 66 DOSIMETRIC MODEL

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INTRODUCTION

The risk of adverse health effects occurring in an individual is commonly evaluated by means of long-term measurements performed using passive integrated radon monitors, since the measured average radon concentrations are, in this case, less influenced by short-term variations. A dose conversion factor per unit radon exposure is therefore needed for the purposes of performing dose assessments.

In the estimation of the dose conversion factor, it is assumed that there is a negative correlation between the equilibrium factor, F, and the unattached fraction, f_p, which can be expressed by means of the equations proposed by different authors which follow:

Power: $$f_p = a_1 \, F^{b_1} \qquad [1] \qquad (1)$$

Log-power: $$\ln[1/f_p] = a_2 \, (\ln[1/F])^{b_2} \qquad [2] \qquad (2)$$

Sum of two exponentials: $$f_p = a_3 \exp(-b_3 F) + c_3 \exp(-d_3 F) \qquad [3] \qquad (3)$$

where a_1, b_1, a_2, b_2, a_3, b_3, c_3 and d_3 are estimated by means of experimental data.

A simplified dosimetric model of the human respiratory tract, in which the dose conversion factor is dependent on the values for F and f_p, is used for the purposes of dose estimation. The dose conversion factor, E, is calculated on the basis of the following equation:

$$E = w_T \, w_R \, F \left[f_p \, D_u + (1 - f_p) \, D_a \right] \qquad (4)$$

where E is the effective dose per unit exposure to radon, w_T is the weighting factor for the lung, w_R is the weighting factor for alpha radiation, D_u is the dose per unit of equilibrium-equivalent concentration (EEC) exposure due to unattached particles and D_a is the dose per unit of equilibrium-equivalent concentration exposure due to attached particles.

Various previously performed studies [1], [4] and [5] show that dose is, in indoor environments, relatively independent of the equilibrium factor. As a consequence, the dose was more closely related to radon exposure rather than to radon progeny exposure, and thus it was only necessary to measure the radon concentration for dose estimation.

The aim of this work was to analyse the dose conversion factor per unit exposure to radon and radon progeny using the three expressions (Equations 1,2 and 3), defining the correlation for F-f_p, with this subsequently being with the data obtained under the RARAD European research programme [6]. The ICRP publication 66 [7] dosimetric model is used in order to evaluate the dependence of this on the equilibrium factor.

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Long-Term Measurements of Equilibrium Factor and Unattached Fraction of Short-Lived Radon Decay Products in a Dwelling—Comparison with Praddo Model

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According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993), the dose due to the inhalation of radon decay products represents almost 50% of the total natural radiation dose to the general population. The scientific community is interested in the assessment of the risk induced by domestic radon exposure. The dosimetric models used to estimate the dose are very sensitive to unattached fraction and size distributions, which makes the characterization of the indoor radon decay products aerosol necessary. For this purpose, long-term measurements of unattached fraction (f_p) and equilibrium factor (F) were taken in a dwelling under typical indoor domestic aerosol conditions. An original device consisting of an annular diffusion channel set in parallel with an open filter was developed and calibrated to continuously measure the unattached fraction. Moreover, radon activity concentration and particle concentration were simultaneously monitored. With aged aerosol, particle concentration was found to be very low (between 500 and 5000 cm^{-3}), radon activity concentration ranged from 240 to 2800 Bq m^{-3}, and the mean values of f_p and F were, respectively, 0.31 (0.08–0.67) and 0.16 (0.04–0.45). With aerosol sources, the high increase in particle concentration led to a negligible unattached fraction and raised the equilibrium factor. A correlation relationship was determined between these two parameters under different aerosol conditions. Finally, our experimental results were compared to results obtained with the PRADDO model; this comparison showed a good agreement between these two different approaches.

halation, it decays into a series of solid short-lived decay products, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 1993), the dose due to inhalation of radon decay products represents almost 50% of the total natural radiation dose to the general population. An association between an excess risk of lung cancer and exposure to radon and its decay products has been demonstrated in uranium miners and other miners (Lubin et al. 1994). The risk related to indoor domestic exposure has been estimated from the risk projection from underground miners data in association with measurements of indoor radon concentrations. However, exposure conditions in mines generally differ from those in dwellings, and thus the role of radon domestic exposure in the occurrence of lung cancer remains unclear.

The last European program, RARAD (1996–1999), was aimed at assessing the risk induced by inhalation of short-lived radon decay products under genuine living conditions. For this purpose, a multidisciplinary approach was chosen, and the studies addressed five main topics: radioactive aerosol, modeling, humans, animals, and retrospective assessment of radon exposure. As part of the aerosol group, our objective was to determine the properties and behavior of the radon decay products under typical domestic conditions and to focus especially on the tem-