Radiological Protection

For practical purposes of assessing and regulating the hazards of ionizing radiation to workers and the general population, ***weighting factors*** are used.

A radiation weighting factor is an estimate of the effectiveness per unit dose of the given radiation relative a to low-LET standard.

Gy (joule/kg) can be used for any type of radiation.
Gy does **not** describe the biological effects of the different radiations.

Weighting factors are dimensionless multiplicative factors used to convert physical dose (Gy) to equivalent dose (Sv) ; i.e., to place biological effects from exposure to different types of radiation on a common scale.

A weighting factor is not an RBE.

Weighting factors represent a conservative judgment of the envelope of experimental RBEs of practical relevance to low-level human exposure.

Radiation Weighting factors

Radiation Type and Energy Range	**Radiation Weighting Factor, W_R**
X and γ rays, all energies	1
Electrons positrons and muons, all energies	1
Neutrons:	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, (other than recoil protons) and energy > 2 MeV,	2-5
α particles, fission fragments, heavy nuclei	20

[ICRU 60, 1991]

For radiation types and energies not listed in the Table above, the following relationships are used to calculate a weighting factor.

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[ICRP, 1991]

$Q = 1.0$	$L < 10$ keV/µm
$Q = 0.32\,L - 2.2$	$10 \leq L \leq 100$ keV/µm
$Q = 300/(L)^{1/2}$	$L \geq 100$ keV/µm

L = unrestricted LET in water (keV/ µm)

Radiation	Typical LET values
1.2 MeV ^{60}Co gamma	0.3 keV/µm
250 kVp x rays	2 keV/µm
10 MeV protons	4.7 keV/µm
150 MeV protons	0.5 keV/µm
14 MeV neutrons	12 keV/µm
Heavy charged particles	100-2000 keV/µm
2.5 MeV alpha particles	166 keV/µm
2 GeV Fe ions	1,000 keV/µm

Tissue weighting factors

Tissue	Tissue Weighting Factor, W_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder	0.05

(ICRU 60, 1991; NCRP 116, 1993)

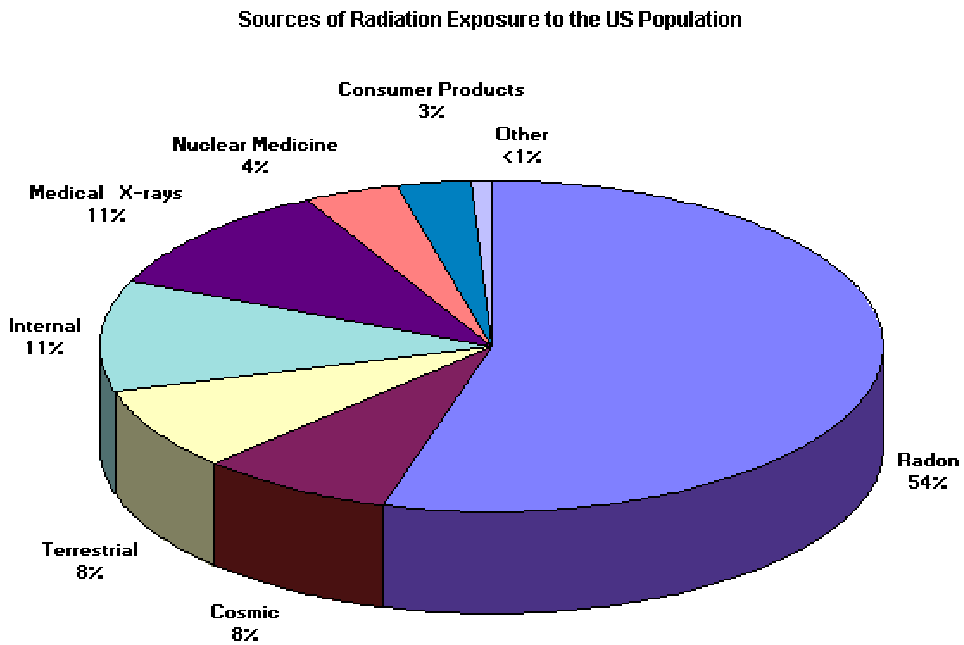
Dosimetric Quantities

Quantity	Definition	New Units	Old Units
Exposure	Charge per unit mass of air 1 R = 2.58 x 10^{-4} C/kg	---	Roentgen (R)
Absorbed dose to tissue T from radiation of type R $D_{T,R}$	Energy of radiation R absorbed per unit mass of tissue T 1 rad = 100 ergs/g 1 Gy = 1 joule/kg 1 Gy = 100 rads	gray (Gy)	Radiation absorbed dose (rad)
Equivalent dose to tissue T H_T	Sum of contributions of dose to T from different radiation types, each multiplied by the radiation weighting factor (w_R) $H_T = \Sigma_R \; w_R \; D_{T,R}$	Sievert (Sv)	Roentgen equivalent man (rem)
Effective Dose E	Sum of equivalent doses to organs and tissues exposed, each multiplied by the appropriate tissue weighting factor (w_T) $E = \Sigma_T \; w_T \; H_T$	Sievert (Sv)	rem

Committed Equivalent Dose: for radionuclides incorporated into the body, the integrated dose over time. 50 years for occupational exposure, 70 years for members of the general public.

Committed Effective Dose: effective dose integrated over 50 or 70 years.

Sources of Radiation Exposure



Annual average in U.S.

3.6 mSv

Other 1%: Occupational; Fallout; Nuclear Fuel Cycle; Miscellaneous

Annual estimated average effective dose equivalent received by a member of the population of the United States.

Source	Average annual effective dose	
	(μSv)	(mrem)
Inhaled (Radon and Decay Products)	2000	200
Other Internally Deposited Radionuclides	390	39
Terrestrial Radiation	280	28
Cosmic Radiation	270	27
Cosmogenic Radioactivity	10	1
Rounded total from natural source	3000	300
Rounded total from artificial Sources	600	60
Total	3600	360

Radioactivity in Nature

Our world is radioactive and has been since it was created. Over 60 radionuclides can be found in nature, and they can be placed in three general categories:

Primordial - been around since the creation of the Earth
Singly-occurring
Chain or series

Cosmogenic - formed as a result of cosmic ray interactions

Primordial radionuclides

When the earth was first formed a relatively large number of isotopes would have been radioactive.

Those with half-lives of less than about 10^8 years would by now have decayed into stable nuclides.

The progeny or decay products of the long-lived radionuclides are also in this heading.

Primordial nuclide examples

Nuclide	Half-life (years)	Natural Activity
Uranium 235	7.04×10^8	0.72 % of all natural uranium
Uranium 238	4.47×10^9	99.27 % of all natural uranium; 0.5 to 4.7 ppm total uranium in the common rock types
Thorium 232	1.41×10^{10}	1.6 to 20 ppm in the common rock types with a crustal average of 10.7 ppm
Radium 226	1.60×10^3	0.42 pCi/g (16 Bq/kg) in limestone and 1.3 pCi/g (48 Bq/kg) in igneous rock
Radon 222	3.82 **days**	Noble Gas; annual average air concentrations range in the US from 0.016 pCi/L (0.6 Bq/m^3) to 0.75 pCi/L (28 Bq/m^3)
Potassium 40	1.28×10^9	Widespread, e.g., soil ~ 1-30 pCi/g (0.037-1.1 Bq/g)

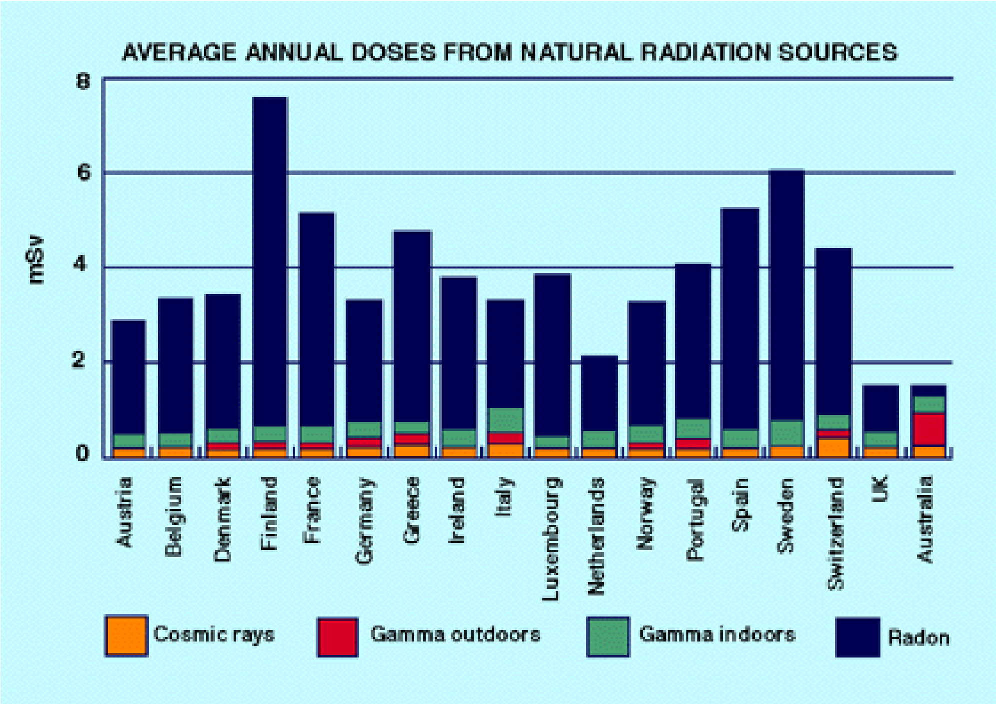
Natural Radioactivity in soil

How much natural radioactivity is found in an area 1 square mile, by 1 foot deep (total volume ~ 7.9×10^5 m^3)?

Activity levels vary greatly depending on soil type, mineral make-up and density (~1.58 g/cm^3). This table represents calculations using typical numbers.

Natural Radioactivity by the Mile

Nuclide	Activity used in calculation	Mass of Nuclide	Activity
Uranium	0.7 pCi/gm (25 Bq/kg)	2,200 kg	0.8 curies (31 GBq)
Thorium	1.1 pCi/g (40 Bq/kg)	12,000 kg	1.4 curies (52 GBq)
Potassium 40	11 pCi/g (400 Bq/kg)	2000 kg	13 curies (500 GBq)
Radium	1.3 pCi/g (48 Bq/kg)	1.7 g	1.7 curies (63 GBq)
Radon	0.17 pCi/gm (10 kBq/m^3) soil	11 µg	0.2 curies (7.4 GBq)



“Single” primordial nuclides

- At least 22 naturally occurring single or nor-series primordial radionuclides have been identified.
- Most of these have such long half-lives, small isotopic and elemental abundances and small biological uptake and concentration that they give little environmental dose.
- The most important is potassium-40. Potassium is a metal with 3 natural isotopes, 39, 40 and 41. Only ^{40}K is radioactive and it has a half life of 1.26 x 10^9 years.

Chain or series-decaying primordial radionuclides

Radioactive series refers to any of four independent sets of unstable heavy atomic nuclei that decay through a sequence of alpha and beta decays until a stable nucleus is achieved.

Three of the sets, the **thorium** series, **uranium** series, and **actinium** series, called natural or classical series, are headed by naturally occurring species of heavy unstable nuclei that have half-lives comparable to the age of the elements.

Important points about series-decaying radionuclides

- 3 main series
- the fourth (neptunium) exists only with man-made isotopes, but probably existed early in the life of the earth
- the 3 main series decay schemes all produce radon (but primary radon source, the longest half-life, is the uranium series).

Series name	Begins	$T_{1/2}$	Ends	Gas ($T_{1/2}$)
Thorium	^{232}Th	1.4 x 10^{10} yr	^{208}Pb	^{220}Rn (55.6 sec) thoron
Uranium	^{238}U	4.5 x 10^9 yr	^{206}Pb	^{222}Rn (3.8 days) radon
Actinium	^{235}U	7.1 x 10^8 yr	^{207}Pb	^{219}Rn (4.0 sec) actinon

Uranium 238 decay scheme.

- Branching occurs when the radionuclide is unstable to both alpha and beta decay, for example, ^{218}Po.
- Gamma emission occurs in most steps.

[Image removed due to copyright considerations]

Major characteristics of the radionuclides that comprise the natural decay series for ^{232}Th, ^{235}U, and ^{238}U

Natural ^{232}Th decay series			Natural ^{235}U decay series			Natural ^{238}U decay series		
Nuclide	Half-life[b]	Principle mode of decay[c]	Nuclide	Half-life[b]	Principle mode of decay[c]	Nuclide	Half-life[b]	Principle mode of decay[c]
^{232}Th	1.4E+10 y	α	^{235}U	7.0E+08 y	α	^{238}U	4.5E+09 y	α
^{228}Ra	5.75 y	β	^{231}Th	1.06 d	β	^{234}Th	24.10 d	β
^{228}Ac	6.13 h	β	^{231}Pa	3.3E+04 y	α	^{234}Pa	1.17 min	β
^{228}Th	1.913 y	α	^{227}Ac	2.2E+01 y	α (1.4 %)	^{234}U	2.5E+05 y	α
					β (98.6 %)			
^{224}Ra	3.66 d	α	^{227}Th	18.7 d	α	^{230}Th	7.5E+04 y	α
^{220}Rn	55.6 s	α	^{223}Fr	21.8 min	β	^{226}Ra	1.6E+03 y	α
^{216}Po	1.5E–02 s	α	^{223}Ra	11.43 d	α	^{222}Rn	3.85 d	α
^{212}Pb	10.64 h	β	^{219}At	56 s	α	^{218}Po	3.1 min	α
^{212}Bi	1.01 h	α (36%)	^{219}Rn	3.96 s	α	^{218}At	1.5 s	α
		β (64%)						
^{212}Po	3.0E–07 s	α	^{215}Bi	7.6 min	β	^{214}Pb	27 min	β
^{208}Tl	3.053 min	β	^{215}Po	1.8E–03 s	α	^{214}Bi	19.9 min	β
^{208}Pb	(stable)	(stable)	^{215}At	1.0E–07 s	α	^{214}Po	1.6E–04 s	α
			^{211}Pb	36.1 min	β	^{210}Tl	1.30 min	β
			^{211}Po	25.2 s	α	^{210}Pb	22.6 y	β
			^{211}Bi	2.14 min	α	^{210}Bi	5.01 d	β
			^{207}Tl	4.77 min	β	^{210}Po	138.4 d	α
			^{207}Pb	(stable)	(stable)	^{206}Hg	8.2 min	β
						^{206}Tl	4.20 min	β
						^{206}Pb	(stable)	(stable)

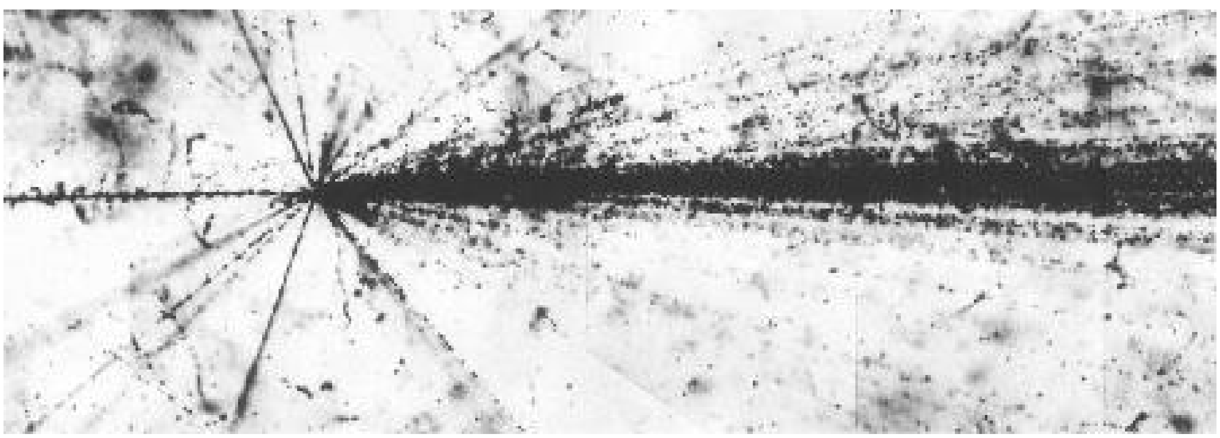
[b] y–years; d–days; h–hours; min–minutes; and s–seconds.
[c] α–alpha decay; β–negative beta decay; EC–electron capture; and IT–isomeric transition (radioactive transition from one nuclear isomer to another of lower energy).

Cosmogenic Radiation

Cosmogenic Nuclides

Nuclide	Half-life	Source	Specific Activity
C-14	5730 yr	Cosmic-ray interactions, $^{14}N(n,p)^{14}C$	~15 Bq/g
Tritium	12.3 yr	Cosmic-ray interactions with N and O; spallation from cosmic-rays, $^{6}Li(n,alpha)^{3}H$	1.2 x 10^{-3} Bq/kg
Be-7	53.28 days	Cosmic-ray interactions with N and O	0.01 Bq/kg

Some other cosmogenic radionuclides are ^{10}Be, ^{26}Al, ^{36}Cl, ^{80}Kr, ^{14}C, ^{32}Si, ^{39}Ar, ^{22}Na, ^{35}S, ^{37}Ar, ^{33}P, ^{32}P, ^{38}Mg, ^{24}Na, ^{38}S, ^{31}Si, ^{18}F, ^{39}Cl, ^{38}Cl, ^{34m}Cl.



Track structure of a cosmic ray collision in a nuclear emulsion

Variations in cosmic ray intensity at the earth’s surface are due to:

- Time: sunspot cycles
- Latitude: magnetic field lines
- Altitude: attenuation in the upper atmosphere

Dose at the surface from cosmic rays

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Internal Radiation

What makes a radionuclide *biologically* important?

- Abundance (both elemental and isotopic)
- Half-life
- Decay scheme (emission type and energy)
- Chemical state
- Chemical behavior in the body
- Does it concentrate?
- Ultimate location
- Rate of excretion

How do the series radionuclides contribute to our dose?

Inhalation
Isotopes of radon (inert gas, but may decay in the lung)
Dust; e.g., our main source of uranium is due to resuspension of dust particles from the earth. Uranium is ubiquitous, a natural constituent of all rocks and soil.

Externally- gamma emission occurs in most decay steps.

Internally-Consumption in food and drinking water

Natural Radioactivity in the body

Nuclide	Total Mass of Nuclide	Total Activity of Nuclide	Daily Intake of Nuclides
Uranium	90 μg	30 pCi (1.1 Bq)	1.9 μg
Thorium	30 μg	3 pCi (0.11 Bq)	3 μg
Potassium 40	17 mg	120 nCi (4.4 kBq)	0.39 mg
Radium	31 pg	30 pCi (1.1 Bq)	2.3 pg
Carbon 14	95 μg	0.4 μCi (15 kBq)	1.8 μg
Tritium	0.06 pg	0.6 nCi (23 Bq)	0.003 pg
Polonium	0.2 pg	1 nCi (37 Bq)	~0.6 μg

It would be reasonable to assume that all of the radionuclides found in your environment would exist in the body in some small amount. The internally deposited radionuclides contribute about 11% of the total annual dose.

Uranium

- Present in all rocks and soil, and thus in both our food and in dust.
- High concentrations in phosphate rocks (and thus in commercial fertilizers).
- Absorbed by the skeleton which receives roughly 3 μSv/year from uranium.

Radium

- Also present in all rocks and soils.
- Food is a more important source of intake
- ^{226}Ra and its daughter products (beginning with ^{222}Rn) contribute the major dose components from naturally occurring internal emitters.
- Dissolves readily, chemically similar to calcium.
- Absorbed from the soil by plants and passed up the food chain to humans
- variations in Ra levels in soil lead to variations in Ra levels in food
- 80% of the total body Ra is in bone (~7mrem/year).
- The rest is uniformly distributed in soft tissue.

Thorium

- Lots in dust but little is incorporated in food
- Thorium is present in the highest concentrations in pulmonary lymph nodes and lung, indicating that the principle source of exposure is due to inhalation of suspended soil particles.
- Ultimately a bone seeker with a long residence time
- Since it is very slowly removed from bone, concentration increases with age.

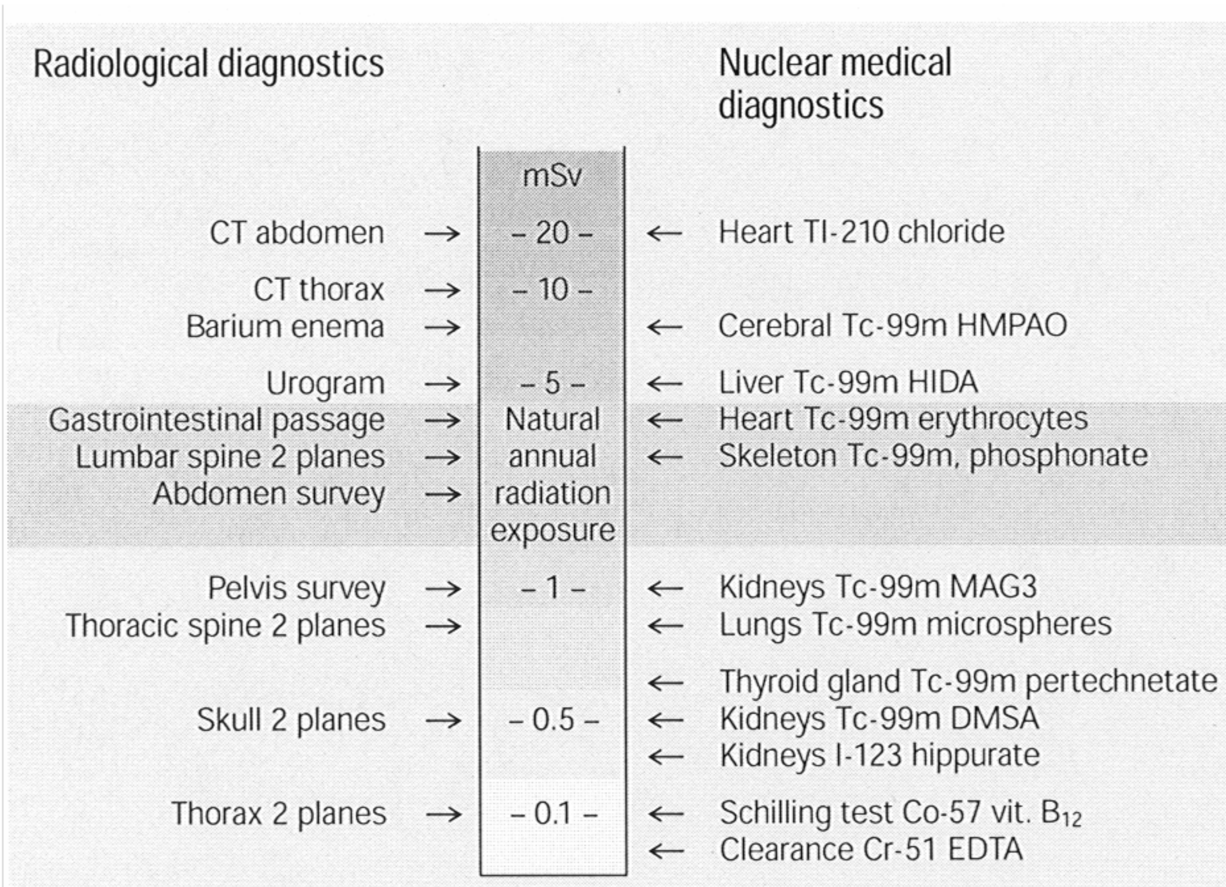
Lead

- Also a bone seeker, half-life in bone is ~ 10^4 days.

Polonium

- Unlike other naturally occurring α-emitters, ^{210}Po deposits in soft tissue not bone.
- Two groups exist for which the dose from ^{210}Po is apt to be exceptionally high.
  - Cigarette smokers
  - Residents of the north who subsist on caribou and reindeer.
- Reindeer eat lichens that absorb trace elements in the atmosphere (^{210}Po and ^{210}Pb). The ^{210}Po content of Lapps living in northern Finland is ~12 times higher than the residents of southern Finland.
- Liver dose in the Laplanders is 170 mrem/year compared to 15 mrem/year for those in the south.

Doses from Medical Applications



Commercial Air Travel

Calculated cosmic ray doses to a person flying in subsonic and supersonic aircraft under normal solar conditions

Route	**Subsonic flight at 36,000 ft (11 km)**			**Supersonic flight at 62,000 (19 km)**		
	Flight duration (hrs)	**Dose per round trip**		**Flight duration (hrs)**	**Dose per round trip**	
		(mrad)	**(μGy)**		**(mrad)**	**(μGy)**
Los Angeles-Paris	11.1	4.8	48	3.8	3.7	37
Chicago-Paris	8.3	3.6	36	2.8	2.6	26
New York-Paris	7.4	3.1	31	2.6	2.4	24
New York-London	7.0	2.9	29	2.4	2.2	22
Los Angeles-New York	5.2	1.9	19	1.9	1.3	13
Sydney-Acapulco	17.4	4.4	44	6.2	2.1	21

Issues:

- Should airline people be considered general public? or radiation workers?
- What about corporate aviation? (altitudes almost as high as supersonic Concorde but travel is sub-sonic and thus time in air is high)
- Business travelers: frequent fliers have no restriction of # hours per year in flight.
- What about pregnant women?
- Should the traveling public be alerted to sunspot activity?
- Is legal action possible?

Table 3. Radiation dose, Los Angeles to Tokyo, supersonic.

Length of flight: 4.083 h
Flight dose equivalent: 26.14 μSv

Personnel	Hours per year	Dose rate mSv y^{-1}
Single flight	4.08	0.03
Frequent flyer	40.83	0.26
Aircrew	700.00	4.48
Pregnant aircrew	156.25	1.00