Natural Radiation
Terrestrial

Physics 6605

2012

Introduction

- Natural radiation has numerous sources
  - Primordial radionuclides
    - Half lives on the order of age of universe - 10^9 to 10^{10} y
  - Decay products of primordial radionuclides
  - Products from spontaneous fission of primordials
  - Activation products from terrestrial neutrons
  - Cosmic radiation
  - Spallation products from cosmic radiation
  - Products from cosmic ray neutron-induced fission
  - Activation products from cosmic neutrons
- We will begin with terrestrial radiation

Primordials

- Important nuclides from dose perspective are a few primordials and their decay products
- All nuclides over mass number 83 are radioactive
- All nuclides over mass number 80 have at least one natural radioactive isotope
- There are about 70 naturally occurring radionuclides

Primordials

- Natural radionuclides are usually divided into
  - Those that occur singly
    - For example potassium-40 and rubidium-87
  - Those that occur in "decay chains" or "decay series"
    - Uranium-238
    - Thorium-232
    - Uranium-235 (actinium)

Geothermal Heat

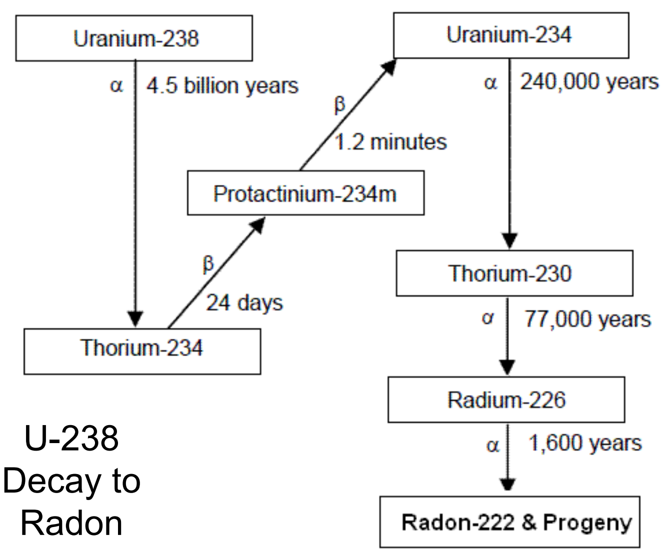
- Heat generated from decay of natural radionuclides, primarily the uranium and thorium chains, can explain the constant heat flow through the surface of the earth of 10^{20} calories/y

Uranium (^{238}U) series

Nuclide	Historical Name	Half Life	Major Radiations
^{238}U	Uranium I	4.47×10^{9} y	alpha, < 1% gamma
^{234}Th	Uranium X_1	24.1 d	beta, gamma
^{234m}Pa	Uranium X_2	1.17 m	beta, < 1% gamma
^{234}U	Uranium II	2.46×10^{5} y	alpha, < 1% gamma
^{230}Th	Ionium	7.54×10^{4} y	alpha, < 1% gamma
^{226}Ra	Radium	1600 y	alpha, gamma
^{222}Rn	Emanation Radon	3.82 d	alpha, < 1% gamma
^{218}Po	Radium A	3.10 m	alpha, < 1% gamma
^{214}Pb	Radium B	26.8 m	beta, gamma
^{214}Bi	Radium C	19.9 m	beta, gamma
^{214}Po	Radium CN	164.3 μs	alpha, < 1% gamma
^{210}Pb	Radium D	22.3 y	beta, gamma
^{210}Bi	Radium E	5.01 d	beta
^{210}Po	Radium F	138.4 d	alpha, < 1% gamma
^{206}Pb	Radium G	Stable	None

Uranium

- Uranium in nature has three isotopes
  - U-238 and U-235 are primordial and head chains
  - U-234 is in the U-238 chain
- U-238 and U-235 exist at a constant ratio in earthen materials with U-235 being 0.71% of U-238 (except for natural reactors)
- U-238 and U-234 tend to be in disequilibrium with excess U-234 in water and deficient U-234 on land



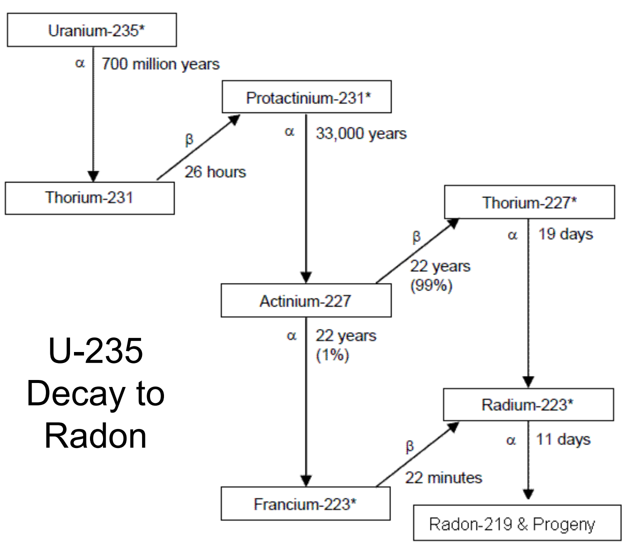
U-238 Decay to Radon

Actinium (U^{235}) series

Nuclide	Historical Name	Half Life	Major Radiations
^{235}U	Actinouranuim	7.04×10^8 y	alpha, gamma
^{231}Th	Uranium Y	1.06 d	beta, gamma
^{231}Pa	Protoactinium	3.28×10^4 y	alpha, gamma
^{227}Ac	Actinium	21.77 y	beta, < 1% gamma
^{227}Th (98.62%)	Radioactinium	18.72 d	alpha, gamma
^{223}Fr (1.38%)	Actinium K	22.0 m	beta, gamma
^{223}Ra	Actinium X	11.44 d	alpha, gamma
^{219}Rn	Emanation Actinon	3.96 s	alpha, gamma
^{215}Po	Actinium A	1.78 ms	alpha, < 1% gamma
^{211}Pb	Actinium B	36.1 m	beta, gamma
^{211}Bi	Actinium C	2.14 m	alpha, gamma
^{207}Tl	Actinium C’	4.77 m	beta, < 1% gamma
^{207}Pb	Actinium D	Stable	None

Uranium

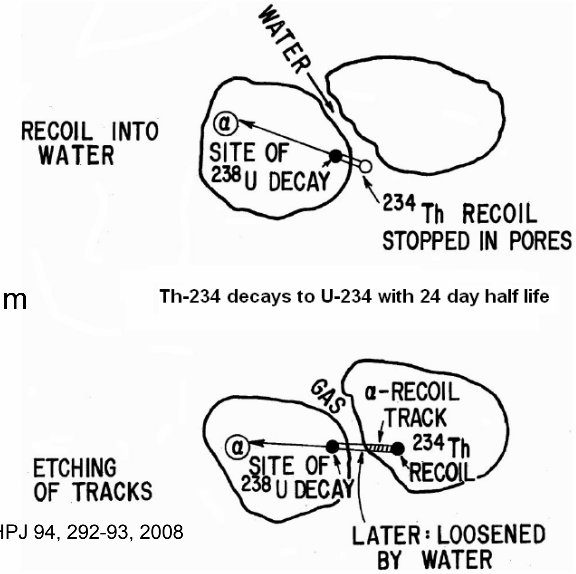
- Uranium is ubiquitous in earth's crust, typically at a few ppm or about 1 pCi/g
- Several materials are notable for high uranium concentrations
  - Ores
  - Shales
  - Phosphate deposits



U-235 Decay to Radon

Material	Potassium-40		Thorium-232		Uranium-238	
	% total K	pCi/g	ppm	pCi/g	ppm	pCi/g
Igneous rocks						
Basalt (crustal ave.)	0.8	8	3-4	0.3-0.4	0.5-1	0.2-0.3
Mafic	1.1	8	2.7	0.3	0.9	0.3
Sialic	4.5	40	20	2.2	4.7	1.6
Granite (crustal ave)	>4	>30	17	1.9	3	1.1
Sedimentary Rocks						
Shale	2.7	20	12	1.4	3.7	1.1
Sandstones						
Clean quartz	<1	<8	<2	<0.2	<1	<0.3
Dirty quartz	2?	11?	3-6?	0.3-0.7?	2-3?	1.0?
Arkose	2-3	15-25	2?	<0.2	1-2?	0.3-0.7?
Beach sands	<1	<8	6	0.7	3	1.1
Carbonate rocks	0.3	2	2	0.2	2	0.7
All Rock (range)[a]	0.3-4.5	2-40	2-20	0.2-2.2	0.5-4.7	0.2-1.6
Continental Crust (ave.)	2.8	23	10.7	1.2	2.8	1.0
Soil (ave.)	1.5	11	9	1.0	1.8	0.6

Uranium Isotope Disequilibrium



Fleischer, R. L., HPJ 94, 292-93, 2008

Radium in water

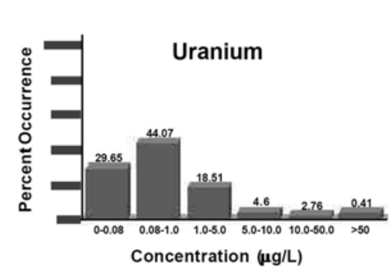
- Uranium and thorium occasionally concentrate in nature
  - Uranium can be concentrated by geochemical processes
  - Thorium, which is less mobile geochemically, is usually concentrated by physical processes
- Radium Concentrations in water first became known in the US around national laboratories such as Argonne in Illinois
- ^{226}Ra and ^{228}Ra have similar distributions of concentration in ground water

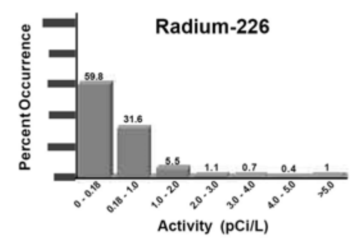
Radium

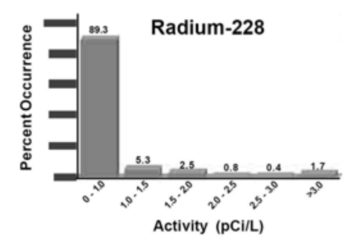
- For natural human radiation exposures, radium is more important than uranium
  - A precursor for γ-emitting nuclides and radon
- Radium is also ubiquitous
  - Higher concentrations in some geologic formations
- In nature, radium is often in approximate equilibrium with uranium but can be separated in industrial processes
  - Deliberately, as in uranium milling
  - Inadvertently, as in phosphate ore processing

Distributions of Natural Radionuclides in Ground Water

[Longtin, J.P. "Occurrence of Radon, Radium, and Uranium in Groundwater," *J. Am. Water Works Assoc.* 80(7):84 (1988)]







Radium in water

- Radium in water is of concern to public health agencies
  - Radium in public drinking water is now regulated, with an associated measuring scheme
- Committed effective dose from drinking water at 25 pCi/l is about 20 mrem in adults and more in younger persons

Thorium

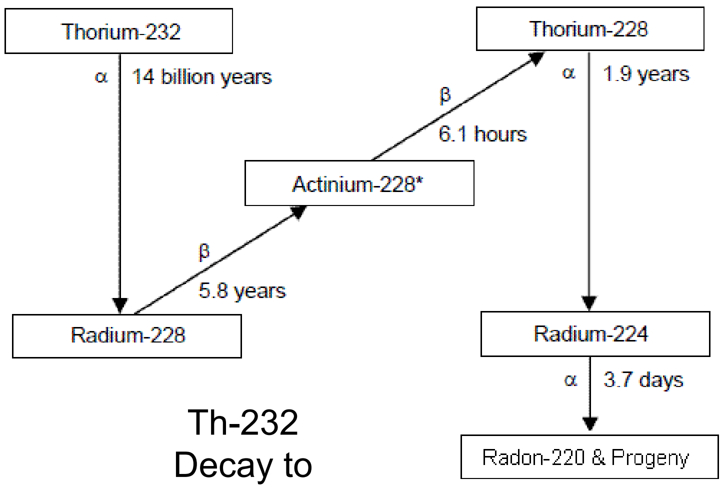
- Thorium is present in nature in greater mass concentrations than uranium
  - longer half-life results in approximately equal activity
- Environmental gamma dose rates are often slightly higher for thorium than uranium
- Thorium in nature is very immobile chemically and is found in biological materials only at very low concentrations
- Highest concentrations in humans occur in pulmonary lymph nodes and are attributed to clearance of inhaled aerosols

Radium in Food

- Radium is also present in foods, notably cereals, nuts and organ meats
  - Radium is exceptionally low in muscle meats, fruits and vegetables
  - The highest concentrations are observed in Brazil nuts
    - 100 to1000 times higher than normal foods
    - Apparently related to affinity for barium on the part of the Brazil nut tree
- Average “body burdens” of Ra-226 vary by about an order of magnitude world-wide

Thorium series

Nuclide	Historical Name	Half Life	Major Radiations
^{232}Th	Thorium	1.41×10^{10} y	alpha, <1%gamma
^{228}Ra	Mesothorium I	5.75 y	beta, <1%gamma
^{228}Ac	Mesothorium II	6.15 h	beta, gamma
^{228}Th	Radiothorium	1.91 y	alpha, gamma
^{224}Ra	Thorium X	3.66 d	alpha, gamma
^{220}Rn	Emanation Thoron	55.6 s	alpha, <1%gamma
^{216}Po	Thorium A	0.145 s	alpha, <1%gamma
^{212}Pb	Thorium B	10.64 h	beta, gamma
^{212}Bi	Thorium C	1.01 h	alpha, gamma
^{212}Po (64%)	Thorium C’	0.300 μs	alpha
^{208}Tl (36%)	Thorium C”	3.05 m	beta, gamma
^{208}Pb	Thorium D	Stable	None



Th-232 Decay to Radon

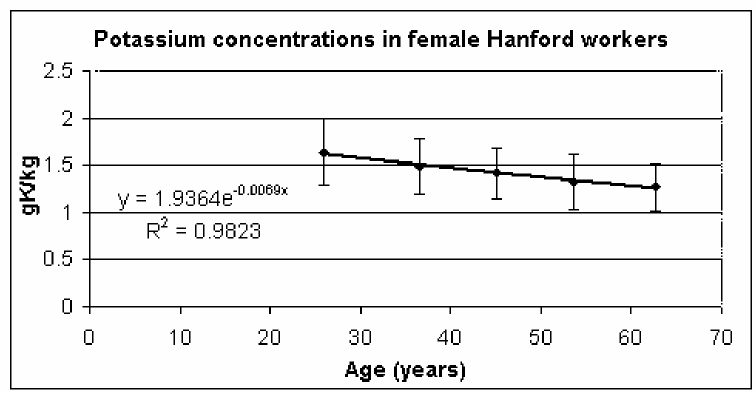
Potassium-40

- K-40 exists as a constant fraction of stable potassium, 0.0118%
- Important contributor to external and internal dose
- Contribution to external dose is variable
  - depends on concentration in rocks and soils
- Contribution to internal dose depends only weakly on intake
  - Depends on biological variability rather than diet
- Fat contains less K than muscle
  - The "fat factor" has been exploited in animal husbandry to assess fat/lean ratios in stock

Material	Potassium-40		Thorium-232		Uranium-238	
	% total K	pCi/g	ppm	pCi/g	ppm	pCi/g
Igneous rocks						
Basalt (crustal ave.)	0.8	8	3-4	0.3-0.4	0.5-1	0.2-0.3
Mafic	1.1	8	2.7	0.3	0.9	0.3
Salic	4.5	40	20	2.2	4.7	1.6
Granite (crustal ave)	>4	>30	17	1.9	3	1.1
Sedimentary Rocks						
Shale	2.7	20	12	1.4	3.7	1.1
Sandstones						
Clean quartz	<1	<8	<2	<0.2	<1	<0.3
Dirty quartz	2?	11?	3-6?	0.3-0.7?	2-3?	1.0?
Arkose	2-3	15-25	2?	<0.2	1-2?	0.3-0.7?
Beach sands	<1	<8	6	0.7	3	1.1
Carbonate rocks	0.3	2	2	0.2	2	0.7
All Rock (range)[a]	0.3-4.5	2-40	2-20	0.2-2.2	0.5-4.7	0.2-1.6
Continental Crust (ave.)	2.8	23	10.7	1.2	2.8	1.0
Soil (ave.)	1.5	11	9	1.0	1.8	0.6

Variation of Potassium Content with Age

(g of K per kg of body weight)



Courtesy of Timothy Lynch

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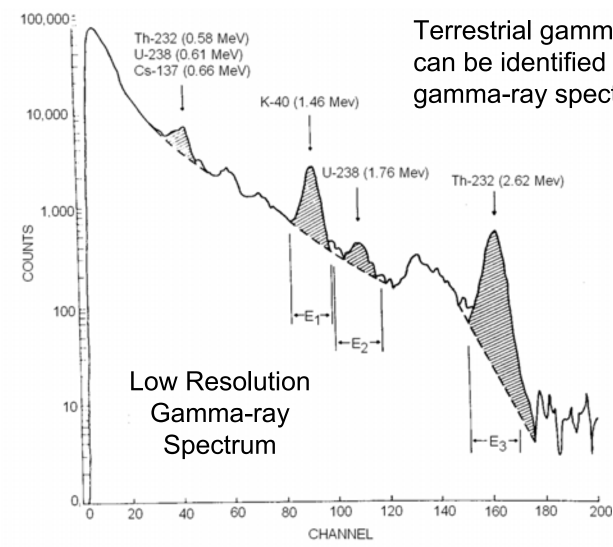
Arkose	2-3	15-25	2?	<0.2	1-2?	0.3-0.7?
Beach sands	<1	<8	6	0.7	3	1.1
Carbonate rocks	0.3	2	2	0.2	2	0.7
All Rock (range)[a]	0.3-4.5	2-40	2-20	0.2-2.2	0.5-4.7	0.2-1.6
Continental Crust (ave.)	2.8	23	10.7	1.2	2.8	1.0
Soil (ave.)	1.5	11	9	1.0	1.8	0.6

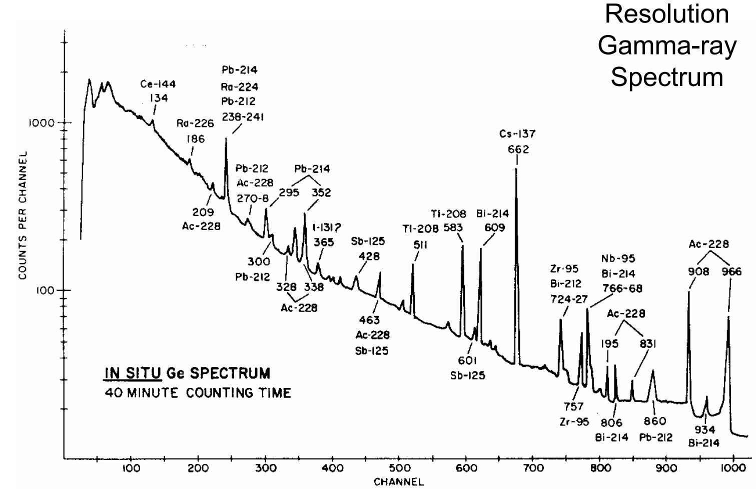
Terrestrial gamma radiation can be identified with gamma-ray spectrometers



Rubidium-87

- Rubidium-87 is a minor beta emitter
- No radioactive decay products
- Contributes less than 1 mrem per year to internal dose

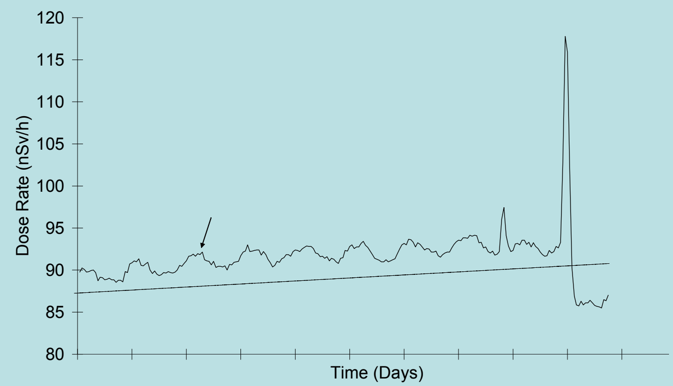
High Resolution Gamma-ray Spectrum



Dose Rates 1 m above Soil

Nuclide	Soil concentration		Absorbed dose rate in air	
	pCi g^{-1}	mBq g^{-1}	mrad y^{-1}	μGy y^{-1}
^{40}K	1	37	1.4	14
^{238}U + decay products	1	37	13.9	139
^{232}Th + decay products	1	37	21.6	216

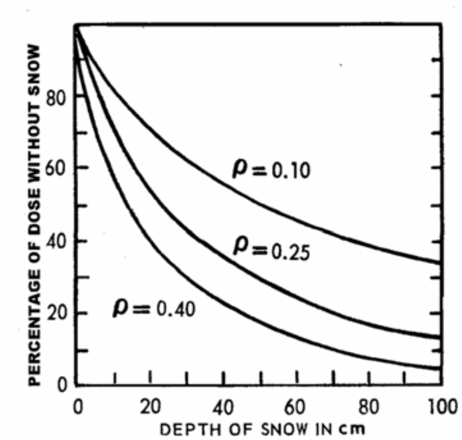
Time Variation of Radiation Near Earth's Surface



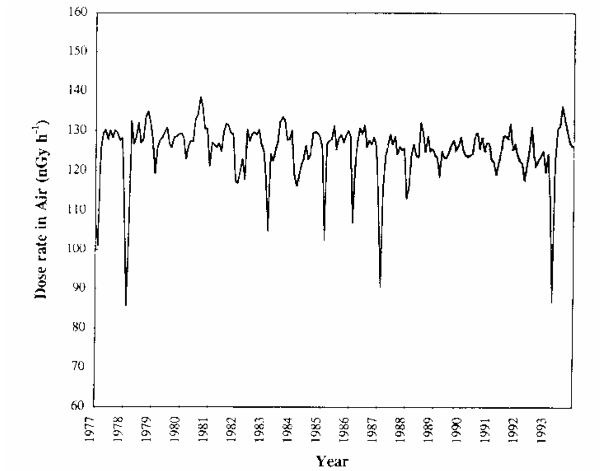
Doses Due to Natural Radiation and Variations

- Charts and tables from NCRP-94 and other sources

Effect of Snow on Dose



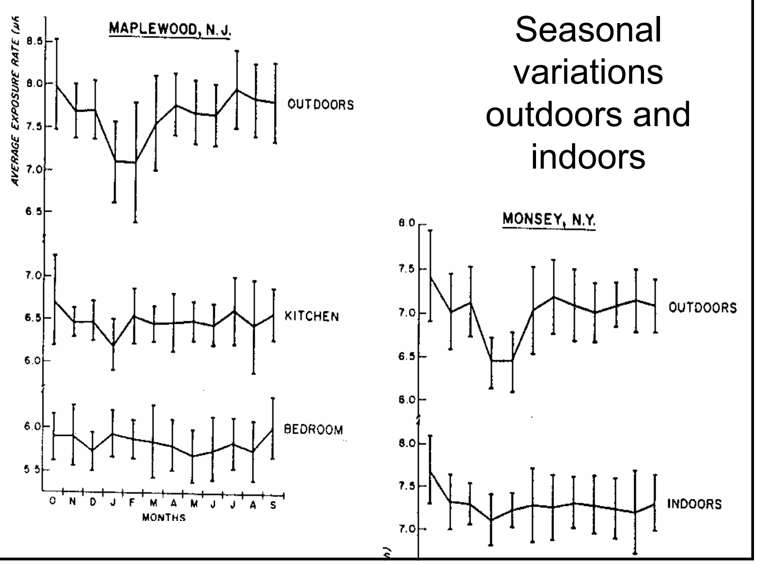
Seasonal Variability of Dose Rate



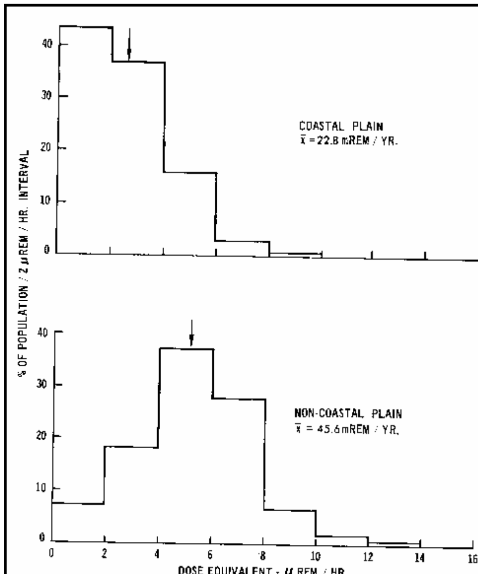
Comparison of Indoor and Outdoor Dose Rates

Building materials (outer walls)	Percent of outdoor absorbed dose rate in air	Remarks
Frame, brick, and stone apartments and houses	Approx. 80–100	17 dwellings
Mostly wood frame	70	160 single homes
Frame	82	5 single homes, 1st floor
Brick	96	1 apartment, 2nd floor
Steel and concrete	87–106	4 office buildings
Mostly wood frame	75	110 single homes

Seasonal variations outdoors and indoors



Dose distributions from ARMS Data



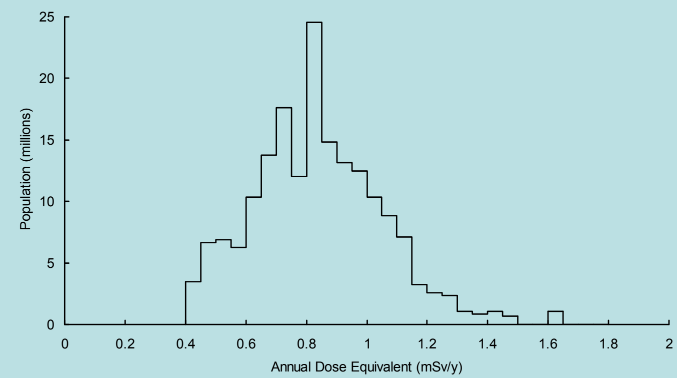
Summary of Population Dose Rates Based on ARMS Data

TABLE 5.7—*Absorbed dose rate in air from terrestrial sources based on population weighted ARMS data*

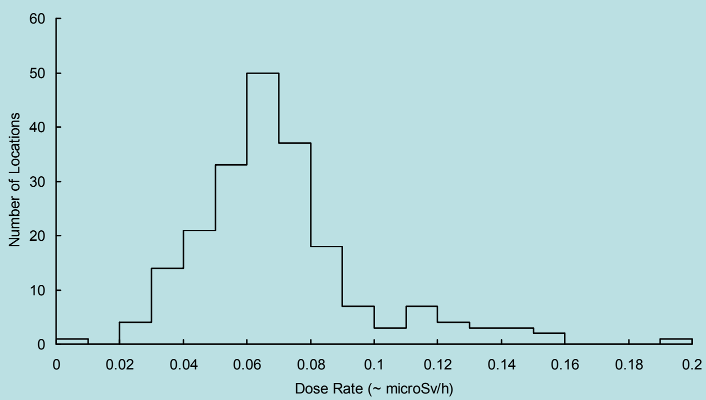
Area	1960 Population covered by ARMS	Absorbed dose rate in air (μGy/y)[a]
Coastal plain	6,759,772	230
Non-coastal plain (excluding Denver)	46,781,330	460
Colorado plateau area (Denver)	1,073,624	900
Population weighted average		440

[a] 1 μGy = 100 μrad.

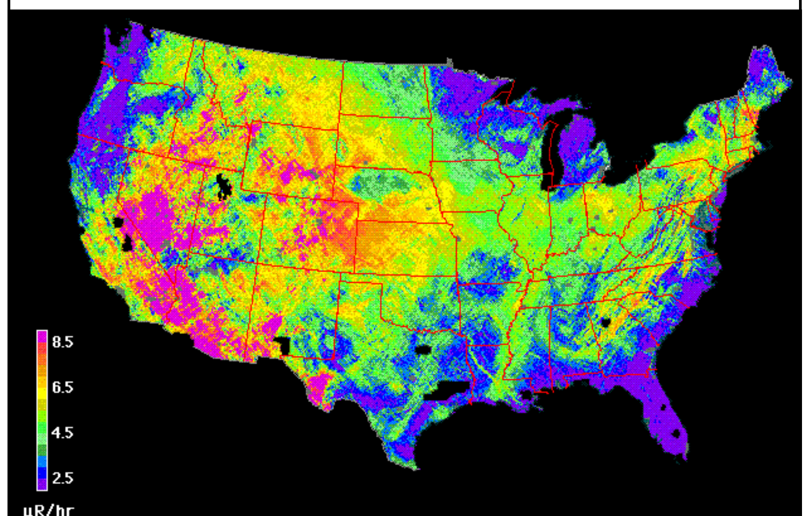
Population Dose Distribution – Cosmic and Terrestrial Only



Terrestrial Dose Rate Distribution from Surface Measurements



Gamma Radiation Data from US Geological Survey

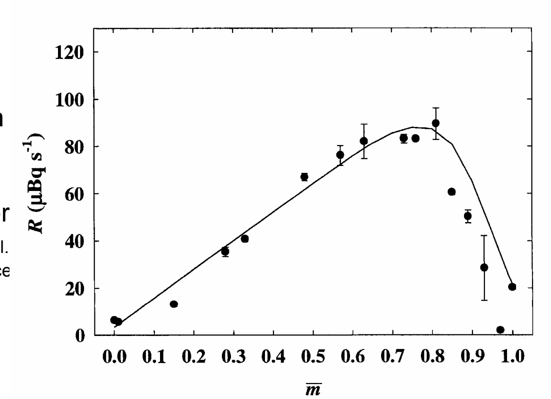


Radon

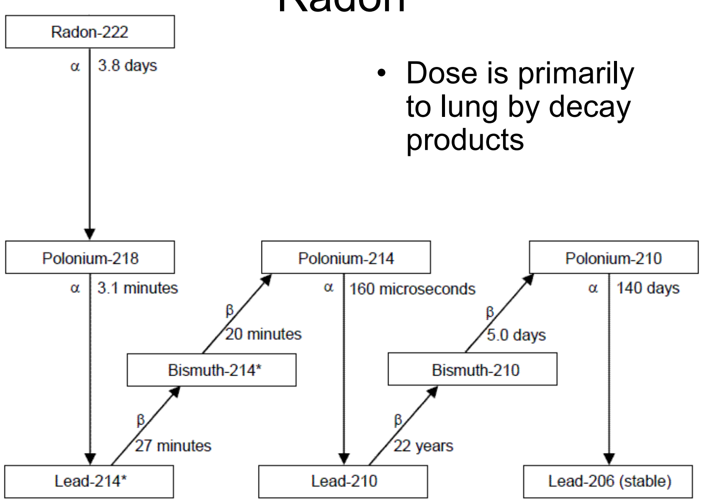
- Radon is a noble gas
  - Can migrate from site of production more easily than any other natural radionuclide
- Consequently it is found in all geological fluids
  - Soil gas
  - Water, including geothermal water
  - Natural gas
  - Petroleum
- Transfer to soil gas is most important for human exposure

Soil Moisture

- Moisture content strongly affects radon transfer from solid to gas in a porous medium such as concrete or soil (Cozmuta et al. Moisture dependence of radon transport in concrete: measurements and modeling, HPJ 85, 438-456)



Radon

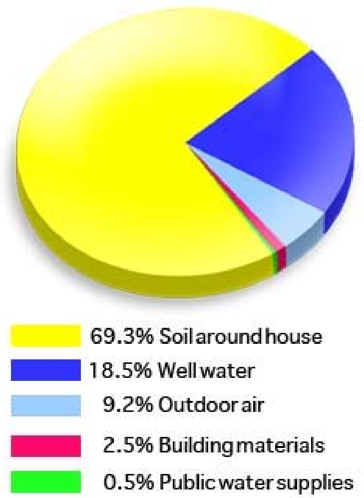


- Dose is primarily to lung by decay products

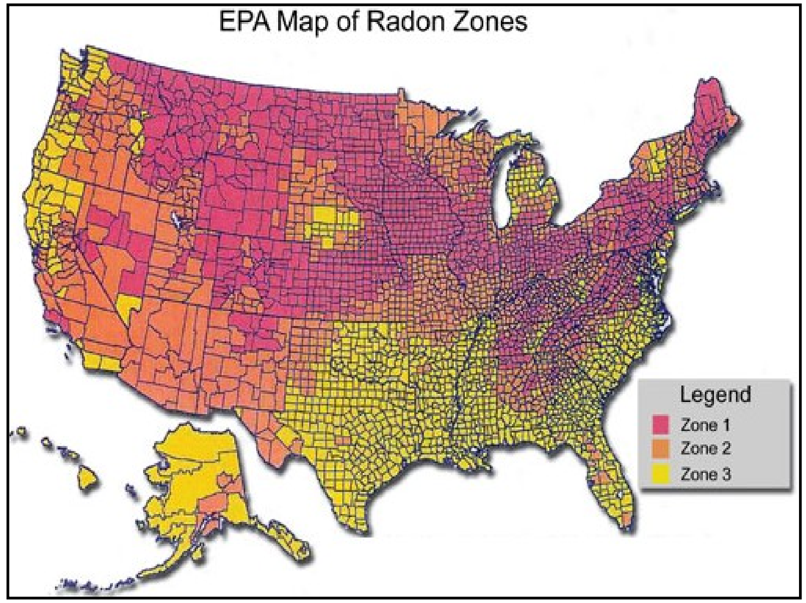
Radon

- Soil gas migrates to atmosphere resulting in variable concentrations
  - Concentrations are controlled outdoors by source term and meteorology
    - primarily atmospheric stability
  - Concentrations indoors are higher due to low air exchange
- Other enclosed spaces have elevated Rn
  - Mines
  - caves

Sources of Indoor Radon

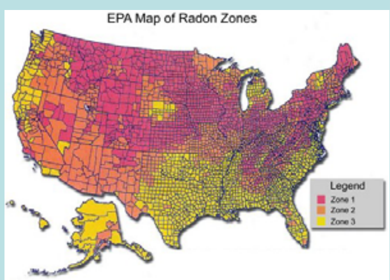


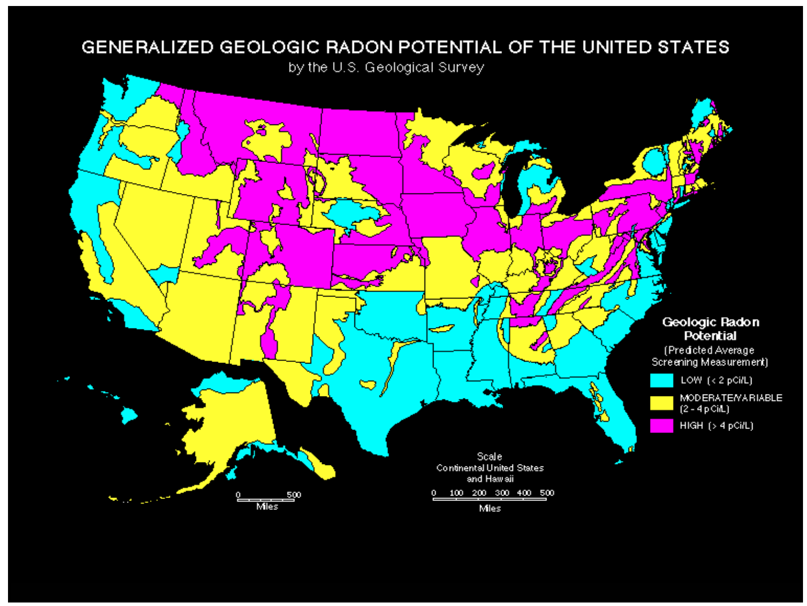
Air Chek, inc



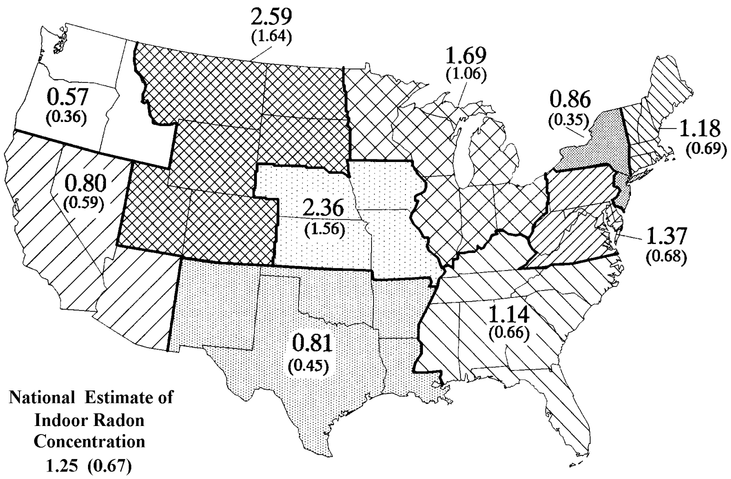
Predicted Average Indoor Radon Screening Level

- Zone 1: greater than 4 pCi/L (red)
- Zone 2: between 2 and 4 pCi/L (orange)
- Zone 3: less than 2 pCi/L (yellow zones)

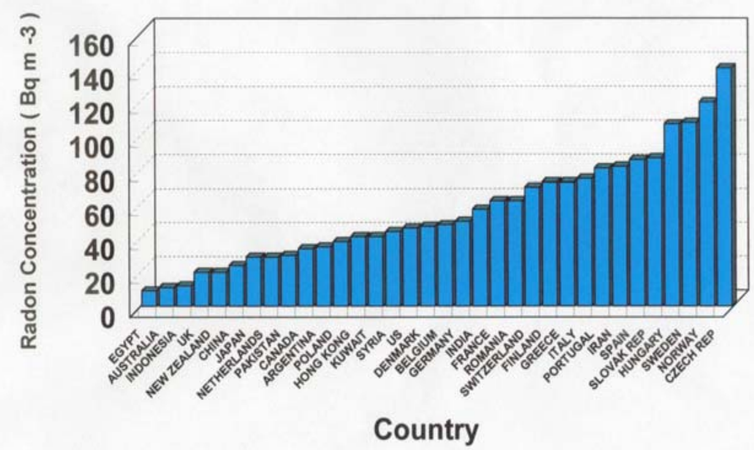




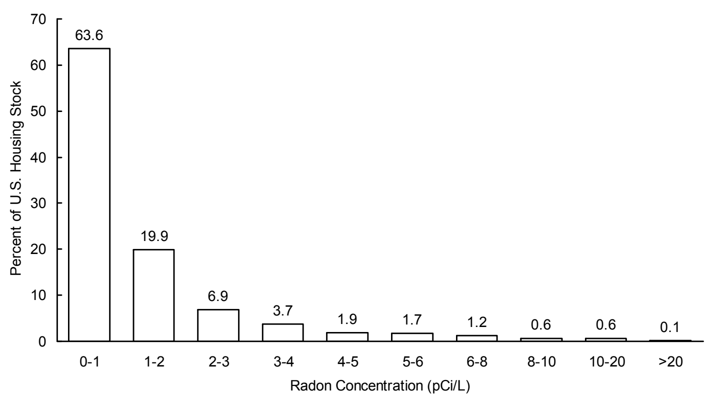
Measured Regional Average Radon (pCi/L)



Radon Concentration in Indoor Surveys



Measured Radon Concentration Distribution in US Residences



Radon Control - USA

- Radon in indoor air is subject only to advisories at the Federal level in US
- An attempt was made by EPA in 2001 to regulate radon in water but was halted as a result of political changes
- Primary control on indoor radon is through real-estate transactions
  - Requirements and guidelines vary from State to State

Variations of ^{210}Pb and ^{210}Po with altitude

Conditions	^{210}Pb concentration ($\mu Bq/m^3$)[a]	^{210}Po concentration ($\mu Bq/m^3$)[a]
Ground level	400	40
Troposphere	120	70
Lower stratosphere	110	100
Stratosphere	150	100

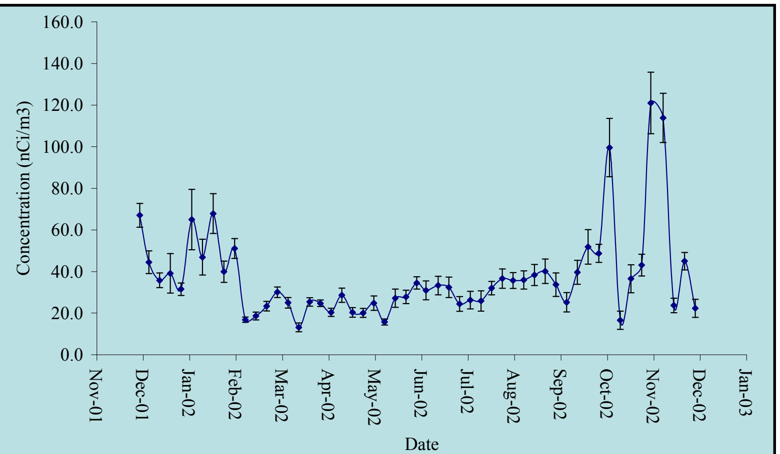
[a] 1 μBq = 27 aCi.

Geographic Variations of ^{210}Pb in Air

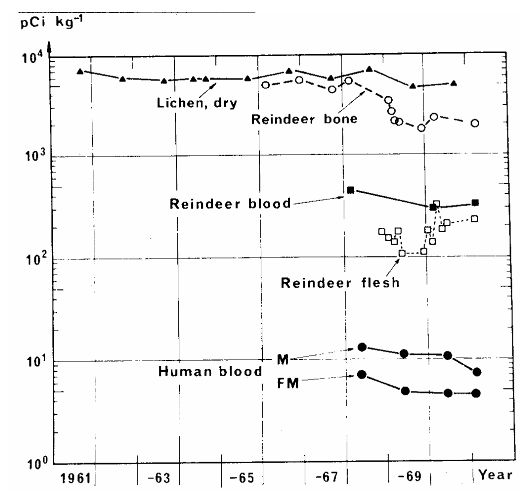
TABLE 6.5—*Geographic variation of concentration of lead-210 in ground level air. All data are means for at least one year*

Location	^{210}Pb concentration ($\mu Bq/m^3$)[a]	Reference
Alaska	300	Magno *et al.* (1970)
California	600	
Florida	300	Patterson and Lockhart (1964)
Hawaii	200	Magno *et al.* (1970)
Hawaii	250	Patterson and Lockhart (1964)
Illinois	1,000	Magno *et al.* (1970)
Illinois	1,500	Golchert *et al.* (1985)
Louisiana	800	Magno *et al.* (1970)
Massachusetts	500	
Massachusetts	700	Shleien and Friend (1966)
Ohio	300	Gold *et al.* (1964)
Puerto Rico	300	Magno *et al.* (1970)
Washington, DC	600	Patterson and Lockhart (1964)

[a] 1 μBq = 27 aCi.



- Variations in time of gross beta activity, a lead-210 surrogate
  - lows in Spring and Summer
  - highs in Fall and Winter
- Peaks correspond to high atmospheric stability in winter



^{210}Po in an Arctic Food Chain

Doses to Lung from Inhaled Radionuclides

Radionuclides	Assumed air concentration	Absorbed dose rate (μGy/y)[b]	Dose Equivalent Rate (μSv/y)[a]	
			Whole lung	Bronchial epithelium
^{238}U-^{226}Ra	0.7 μBq/m^3 (20 aCi/m^3)	0.006		0.1
^{222}Rn	40 Bq/m^3 (1 pCi/l)	10	200	
^{218}Po-^{214}Po	0.004 WL	1,200		24,000
^{210}Po	70 μBq/m^3 (2 fCi/m^3)	0.4		8
^{232}Th-^{224}Ra	0.4 μBq/m^3 (10 aCi/m^3)	0.009		0.2
^{220}Rn	0.2 Bq/m^3 (5 pCi/m^3)	0.005	0.1	
^{212}Pb-^{212}Po	0.07 Bq/m^3 (2 pCi/m^3)	20		400

1 μSv = 100 μrem.
1 μGy = 100 μrad.

Unusual Exposures to Natural Sources and TENORM

- Denver - 50% higher than US average
  - Other areas of western US also elevated
- Grand Junction
  - Structures built with mill tailings
  - Generally elevated indoor and outdoor radon
- Phosphate centers; FL, TN, ID
  - Phosphorus slag used in construction
  - Elevated gamma level
  - Radon levels typically not elevated

Dose to Tissues from Radionuclides in the Body

TABLE 9.2—*Dose equivalent rates to various tissues from natural radionuclides contained in the body*

Radionuclide	Dose equivalent rate (μSv/y)[a, b, c]		
	Soft tissue	Bone surfaces	Bone marrow
^{14}C	10	8	30
^{40}K	180	140	270
^{87}Rb	3	14	7
^{238}U-^{234}Th	4.6	3	0.4
^{230}Th	0.1	6	1
^{226}Ra	3	90	15
^{222}Rn	7	14	14
^{210}Pb-^{210}Po	140	700	140
^{232}Th	0.1	2	0.4
^{228}Ra-^{224}Ra	1.5	120	22
^{220}Rn	<0.1	—	—
Total	350	1,100	500

[a] 1 μSv = 100 μrem.

Reading Prong

- High natural uranium series
- Soil radium concentrations 100 times normal
- Associated high radon
- Location of the infamous "Watrous house" that initiated a sustained concern for radon
  - Discovered because a nuclear plant worker was setting off portal monitors when entering plant

Ontario, Canada

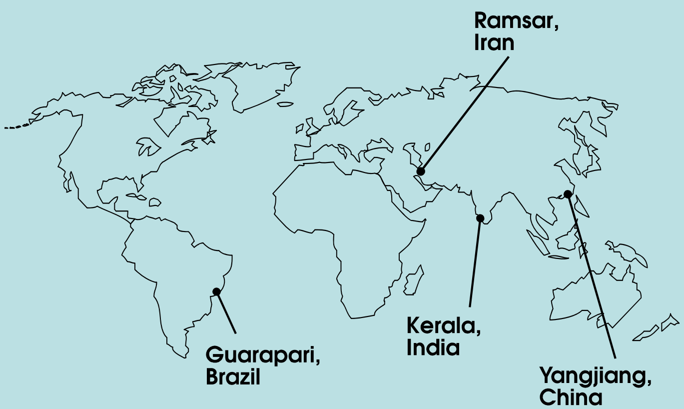
- Several towns have been contaminated
  - Port Hope - uranium/radium processing
  - Scarborough - incineration of radium residues
- Elliot lake - elevated radon from natural and waste sources

1987 annual estimated average effective dose equivalent received by a member of the population of the US from natural radiation*.

Source	Average annual EDE (mrem)
Inhaled (radon and decay products)	200
Cosmogenic radionuclides (e.g., ^{14}C)	1
Other internally deposited radionuclides (e.g., ^{40}K, ^{210}Po)	40
Terrestrial radiation	28
Cosmic radiation	27
Total (rounded)	300

*Adapted from NCRP Report 94, 1987

Well-studied High Background Radiation Areas

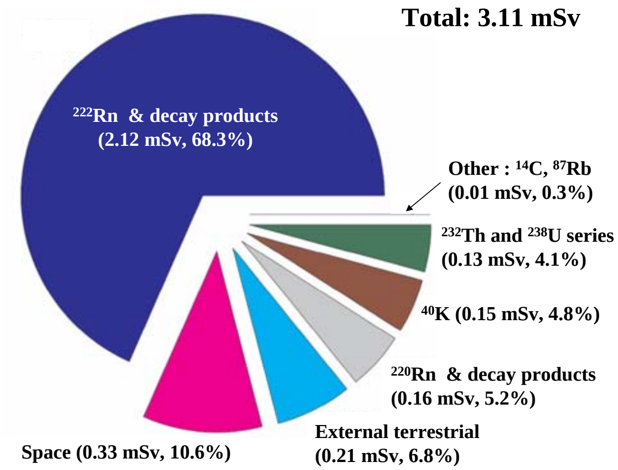


2009 annual estimated average effective dose equivalent received by a member of the population of the US from background radiation*.

Source	Average annual EDE (mrem)
Radon and thoron	228
Other internally deposited radionuclides (e.g., ^{40}K, ^{210}Po)	29
Terrestrial radiation	21
Space radiation	33
Total (rounded)	311

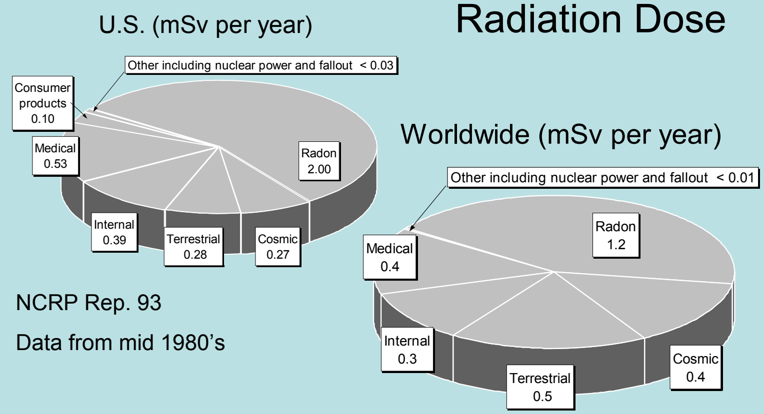
*Adapted from NCRP Report 160, 2009

Background Annual Effective Dose to US Residents



From NCRP Report 160 via Dan Strom

Sources of Radiation Dose



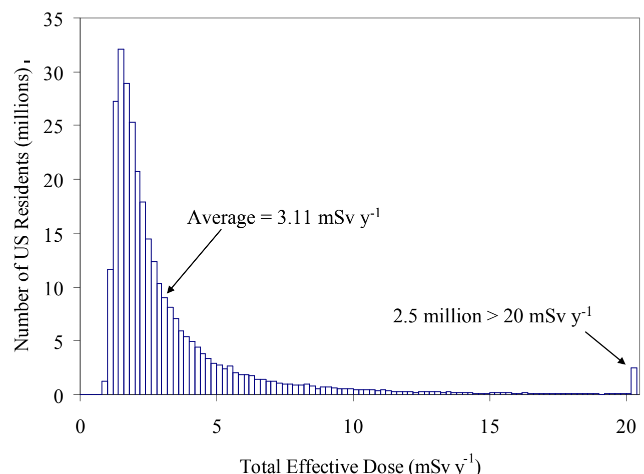
NCRP Rep. 93

Data from mid 1980's

UNSCEAR 2000

Data from late 1990's

Distribution of Annual Effective Dose in the US Population Due to Ubiquitous Background Radiation



Courtesy of Dan Strom

U.S. ~2006 in %
Total Is 6.2 mSv

From NCRP Report 160