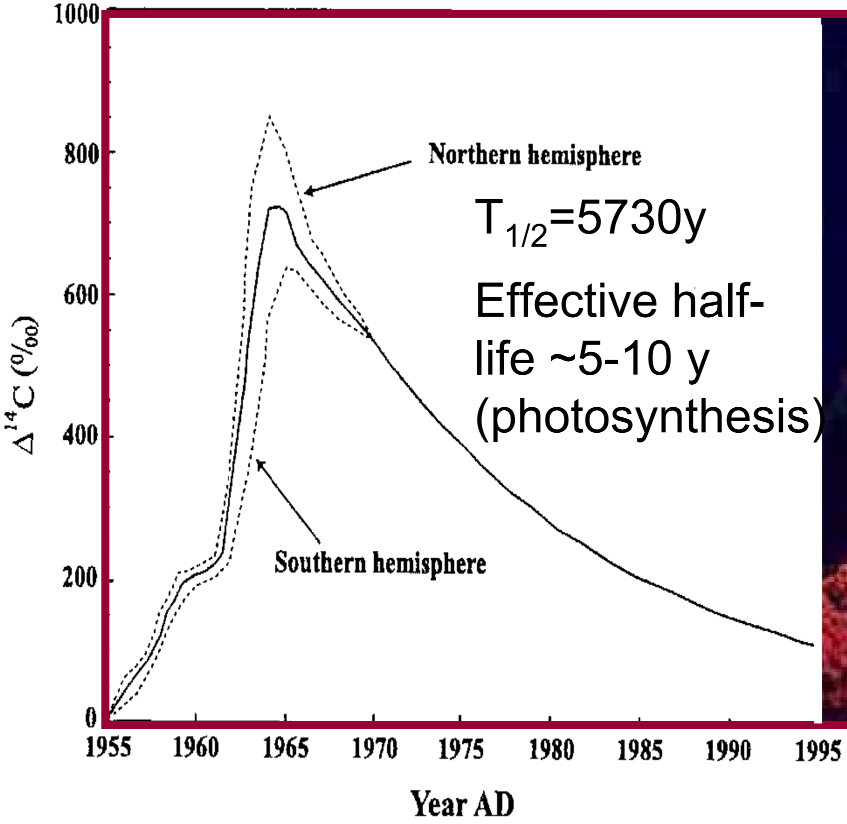
Radiation Effects of a Nuclear Bomb

Beside shock, blast, and heat a nuclear bomb generates high intensity flux of radiation in form of γ-rays, x-rays, and neutrons as well as large abundances of short and long-lived radioactive nuclei which contaminate the entire area of the explosion and is distributed by atmospheric winds worldwide.

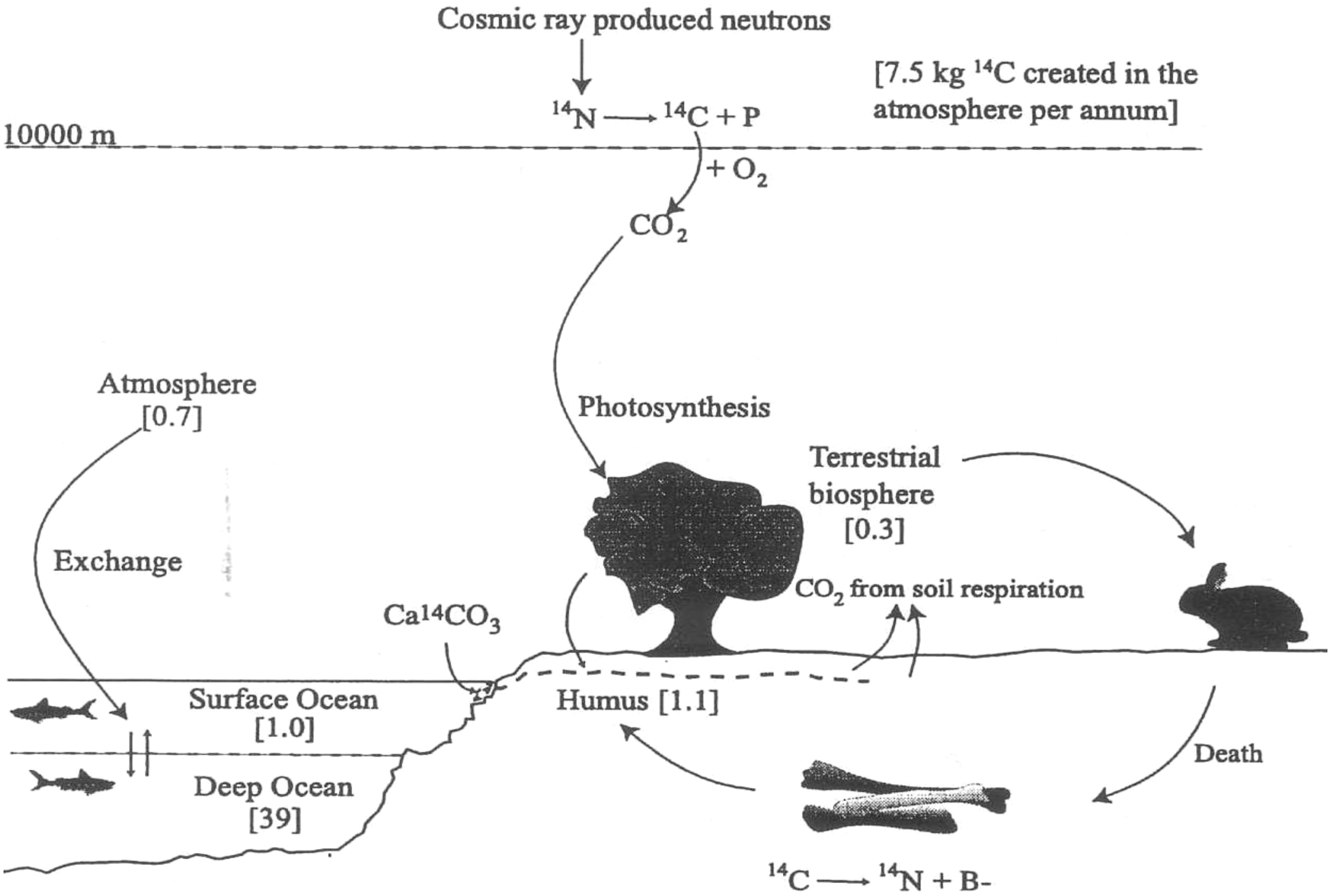


$T_{1/2}$=5730y

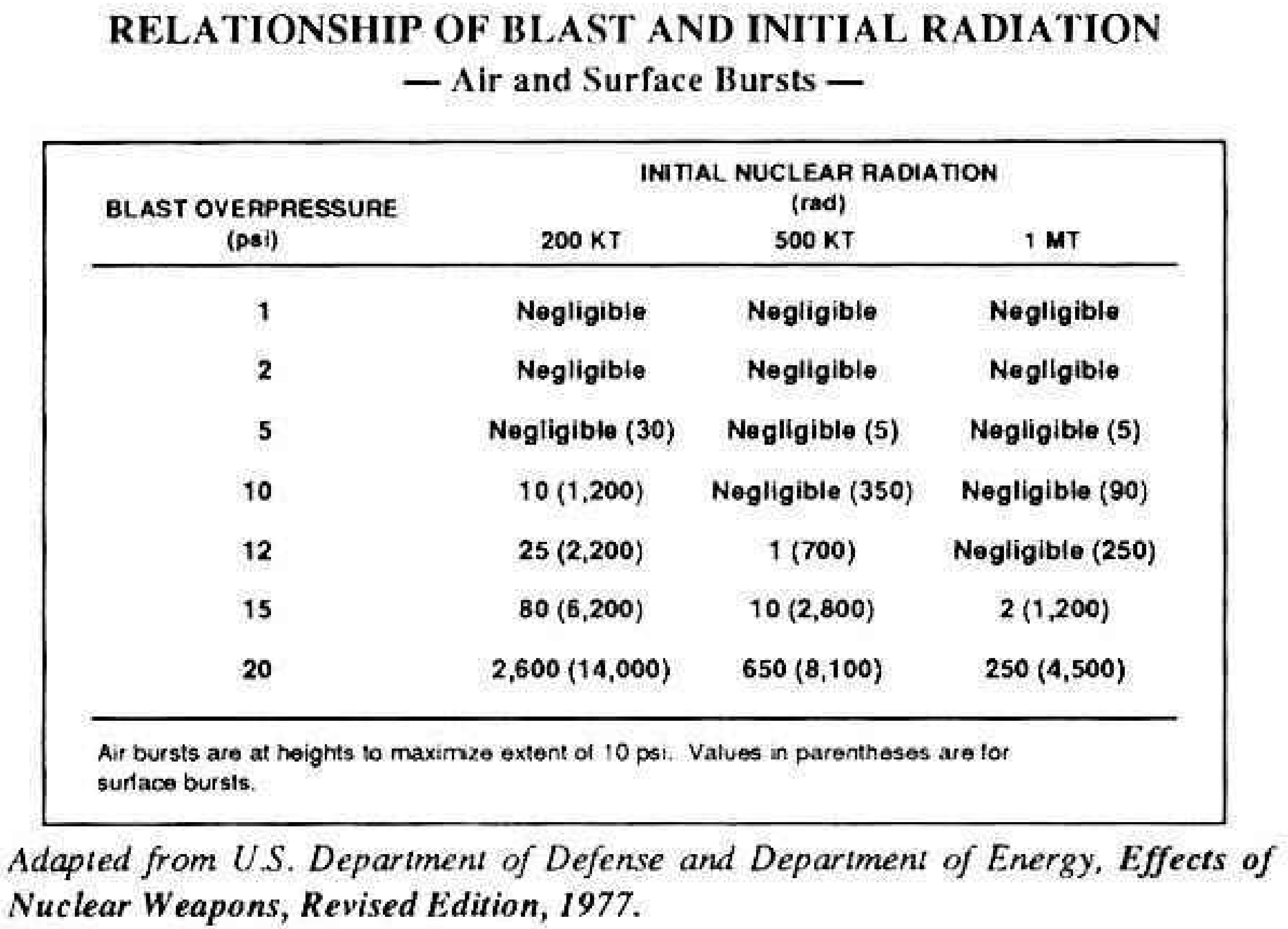
Effective half-life ~5-10 y (photosynthesis)

^{14}C distribution

+ nuclear test related ^{14}C production



Nuclear Bomb related Radiation Production



RELATIONSHIP OF BLAST AND INITIAL RADIATION

— Air and Surface Bursts —

BLAST OVERPRESSURE (psi)	INITIAL NUCLEAR RADIATION (rad)		
	200 KT	500 KT	1 MT
1	Negligible	Negligible	Negligible
2	Negligible	Negligible	Negligible
5	Negligible (30)	Negligible (5)	Negligible (5)
10	10 (1,200)	Negligible (350)	Negligible (90)
12	25 (2,200)	1 (700)	Negligible (250)
15	80 (6,200)	10 (2,800)	2 (1,200)
20	2,600 (14,000)	650 (8,100)	250 (4,500)

Air bursts are at heights to maximize extent of 10 psi. Values in parentheses are for surface bursts.

Adapted from U.S. Department of Defense and Department of Energy, ***Effects of Nuclear Weapons, Revised Edition, 1977.***

The units rad (rem) are a measure of radiation exposure!

Monitoring radiation intensity

Classical Unit: 1 Curie [Ci] $1\left[Ci\right]=\frac{dN}{dt}=3.7\cdot 10^{10}\left[\frac{decays}{s}\right]$

Modern Unit: 1 Becquerel [Bq] $1\left[Bq\right]=\frac{dN}{dt}=1\left[\frac{decay}{s}\right]$

The so-called dosimetry units (rad, rem) determine the amount of damage radioactive radiation can do to the human body. They depend on the kind and nature of the incident radiation

(X-rays, γ-rays, α-particles, β-particle, or neutrons).

It also depends on the energy loss of the particular radiation and the associated ionisation effects in the human body material.

Radiation Detection

Radiation Exposure & Dosimetry

Dose: $$D = \frac{E}{m}$$

Amount of energy *E* deposited by radiation into body part of mass *m*.

unit Rad or Gray

Equivalent Dose: $$H = Q \cdot D$$

Radiation independent dose *Q* is normalization factor which accesses the individual body damage done by the particular kind of radiation

Unit Rem or Sievert

Photons:	Q=1
Neutrons: E<10keV	Q=5
Neutrons: E>10keV	Q=15
Protons:	Q=5
Alphas :	Q=20

UNITS OF RADIATION MEASUREMENT

Dosage units:

The Sievert (Gray) is a measure of biological effect.

1 Gray (Gy) = 1 Joule/kg (Energy/mass)

1 Sievert (Sv) = Gray x Q, where Q is a "quality factor" based on the type of particle.

Q for electrons, positrons, and x-rays = 1 Q = 3 to 10 for neutrons, protons dependent upon the energy transferred by these heavier particles.

Q = 20 for alpha particles and fission fragments.

Converting older units:

1 rad = 1 centigray = 10 milligrays (1 rad = 1cGy = 10 mGy)

1 rem = 1 centisievert = 10 millisieverts (1 rem = 1cSv = 10 mSv)

Nominal background radiation absorbed dose of 100 mrad/year = 1 mGy/yr.

Nominal background radiation dose biological equivalent of 100 mrem/year = 1mSv/yr.

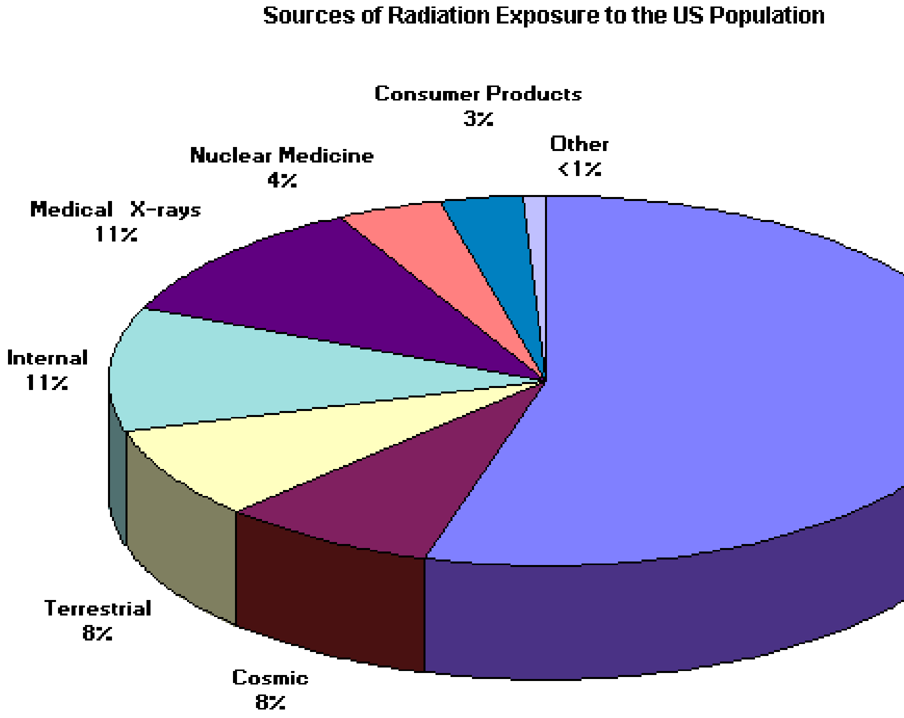
Occupational whole body limit is 5 rem/yr = 50 mSv/yr.

2.5 mrem/hr or 25 uSv/hr is maximum average working level in industry.

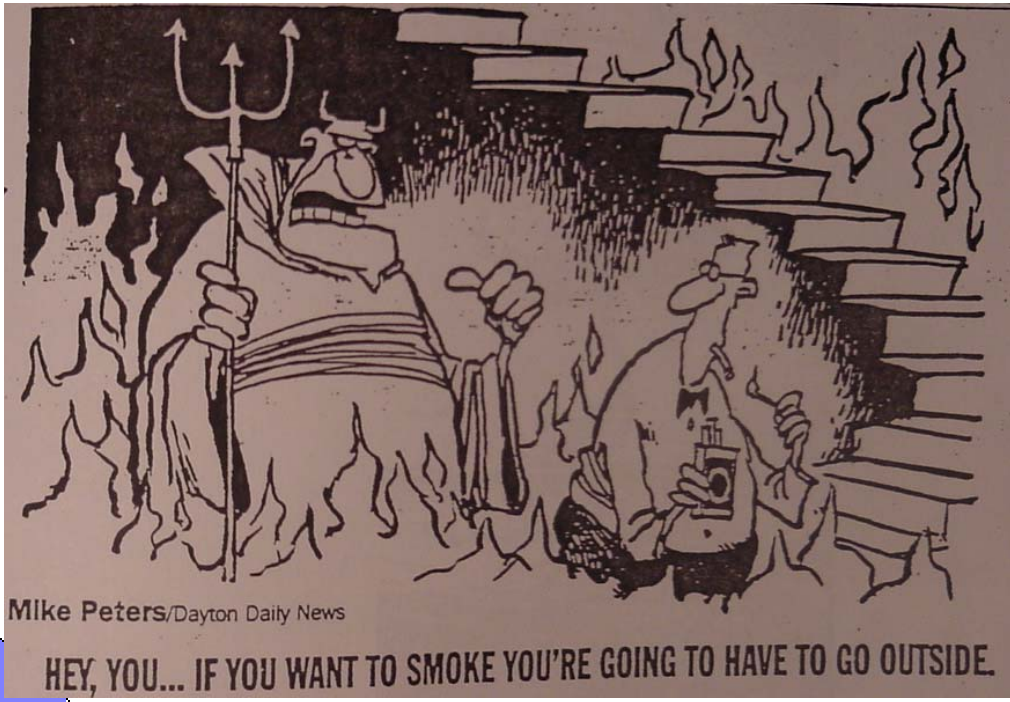
Exposure rate from Naturally Occurring Radioactive Material; an empirically derived conversion factor for Ra-226 decay series: 1.82 microR/ hour = 1 picoCurie/gram.

Exposure to Natural and Man-made Radioactivity

Total average annual dose:
$H \approx 250\text{-}300$ mrem



Average annual dose from nuclear bomb test fallout $H_{fo} \approx 0.06$ mrem.

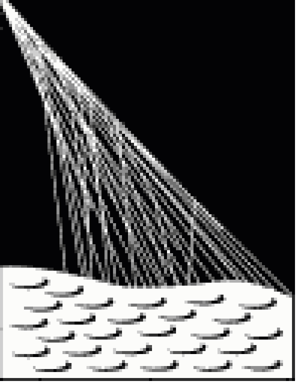


Mike Peters/Dayton Daily News

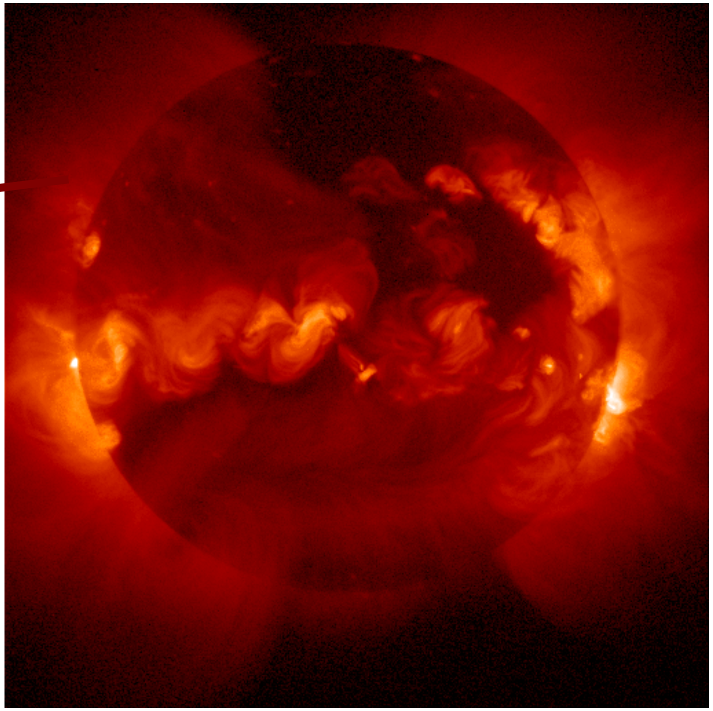
HEY, YOU... IF YOU WANT TO SMOKE YOU'RE GOING TO HAVE TO GO OUTSIDE.

Tobacco contains α-emitter ^{210}Po with $T_{1/2}$=138.4 days. Through absorption in the bronchial system smoking adds 280 mrem/year to the annual dose of US population

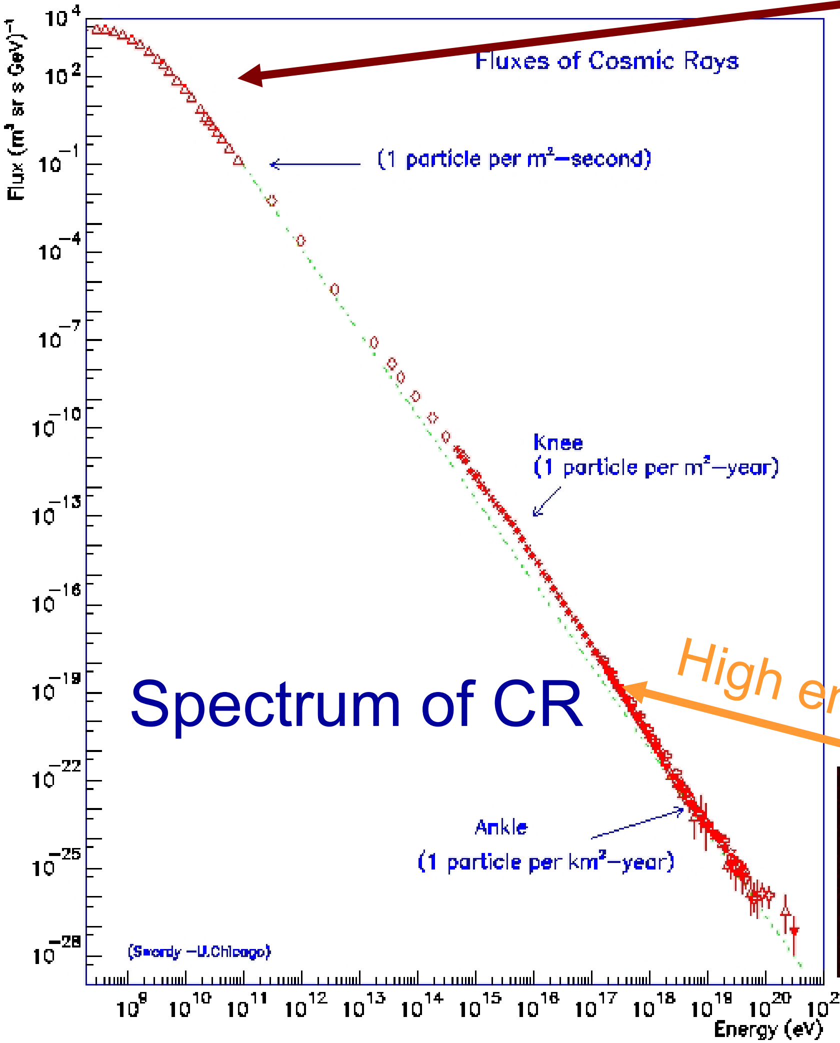
Sources of Natural and Radioactivity



Cosmic Ray Bombardment

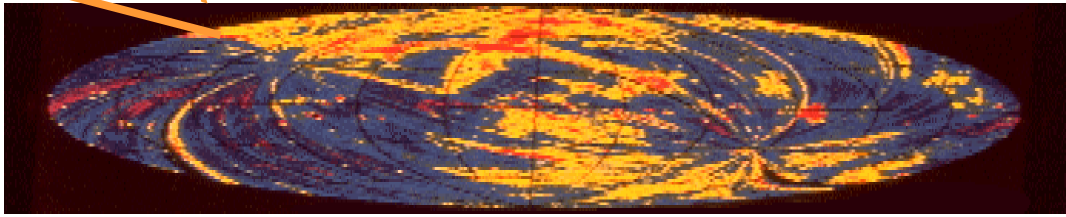


Low energy CR



Spectrum of CR

High energy CR



Cosmic Rays origin from:

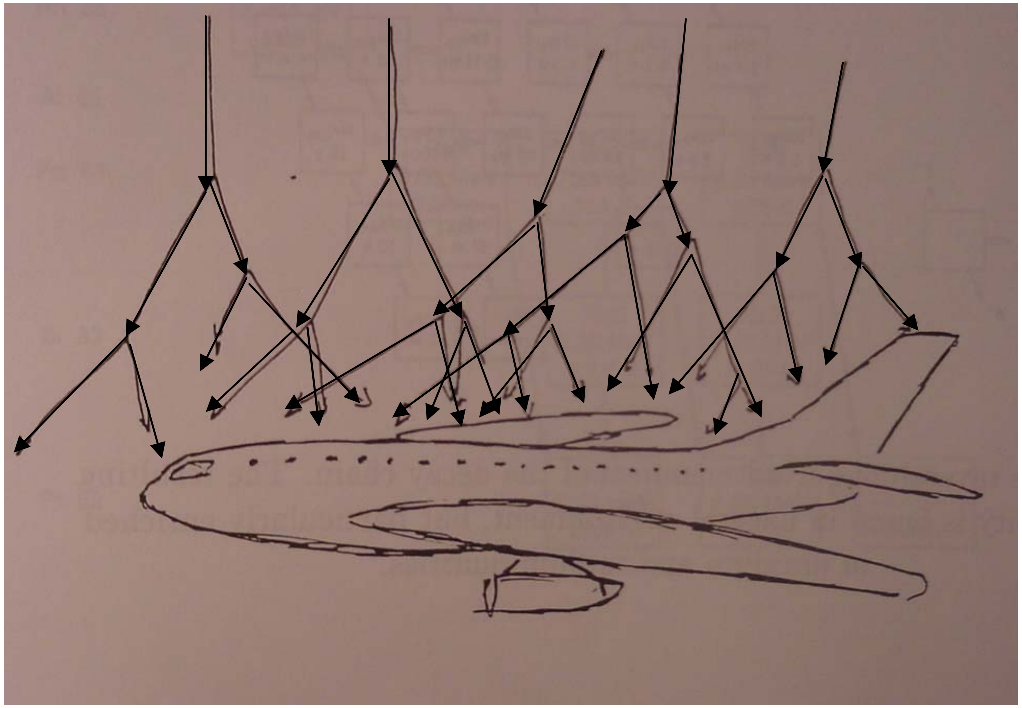
- solar flares;
- distant supernovae;

Cosmic Rays in High Altitude

Earth is relatively protected from cosmic rays through atmosphere shield; typical exposure is H=3.2 mrem/h. Mountain climbers and airline crews and passengers are exposed to higher doses of radiation. Dose doubles every 1500 m in height. At 10 km height dose is about 100 times sea-level dose H=0.32mrem/h.

Example: Total dose H:

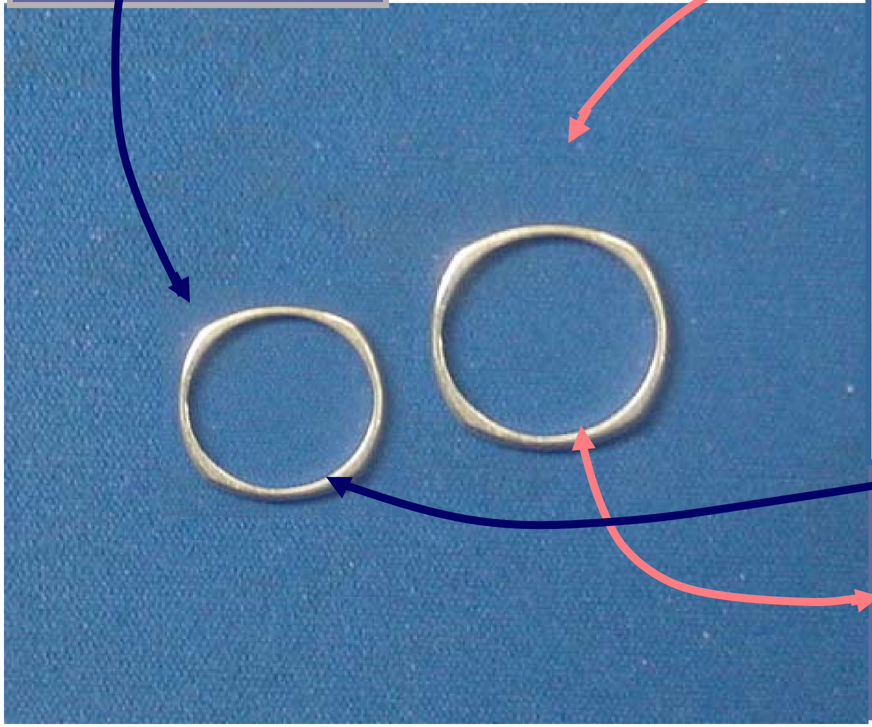
- after 10h of flight:
  H=3.2 mrem,
- for round trip:
  H=6.4 mrem
- Frequent flyer with about
  10 transatlantic flights/year
  H=64 mrem/year.

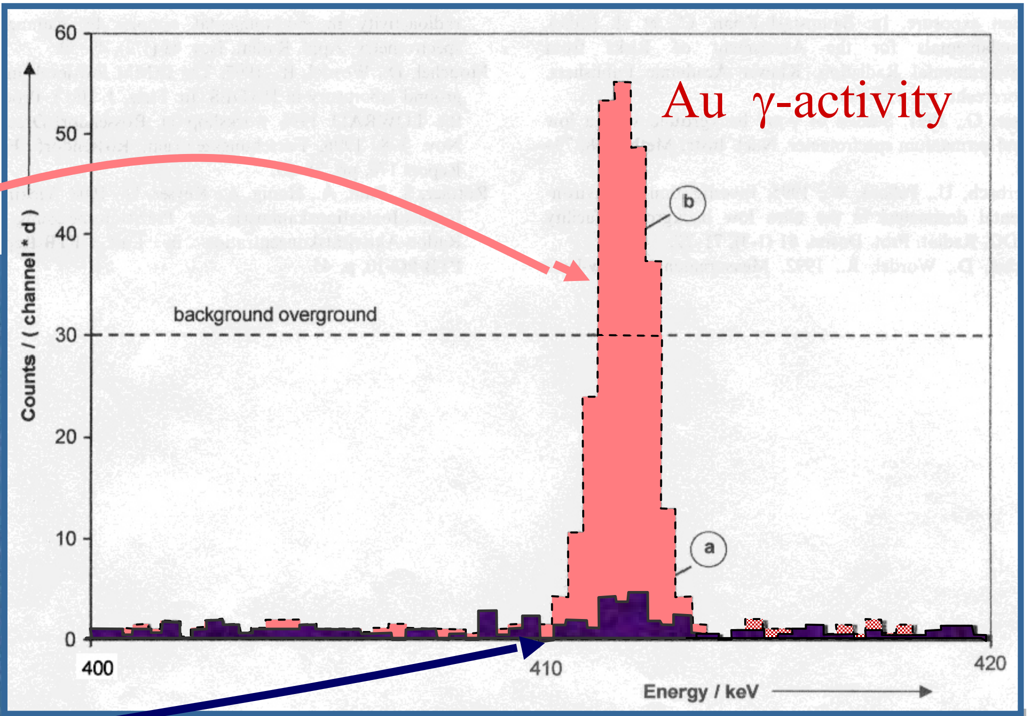


Compare to natural dose (~200 mrem/y) !

Observable Effects!

Wife's ring with ground level dose!

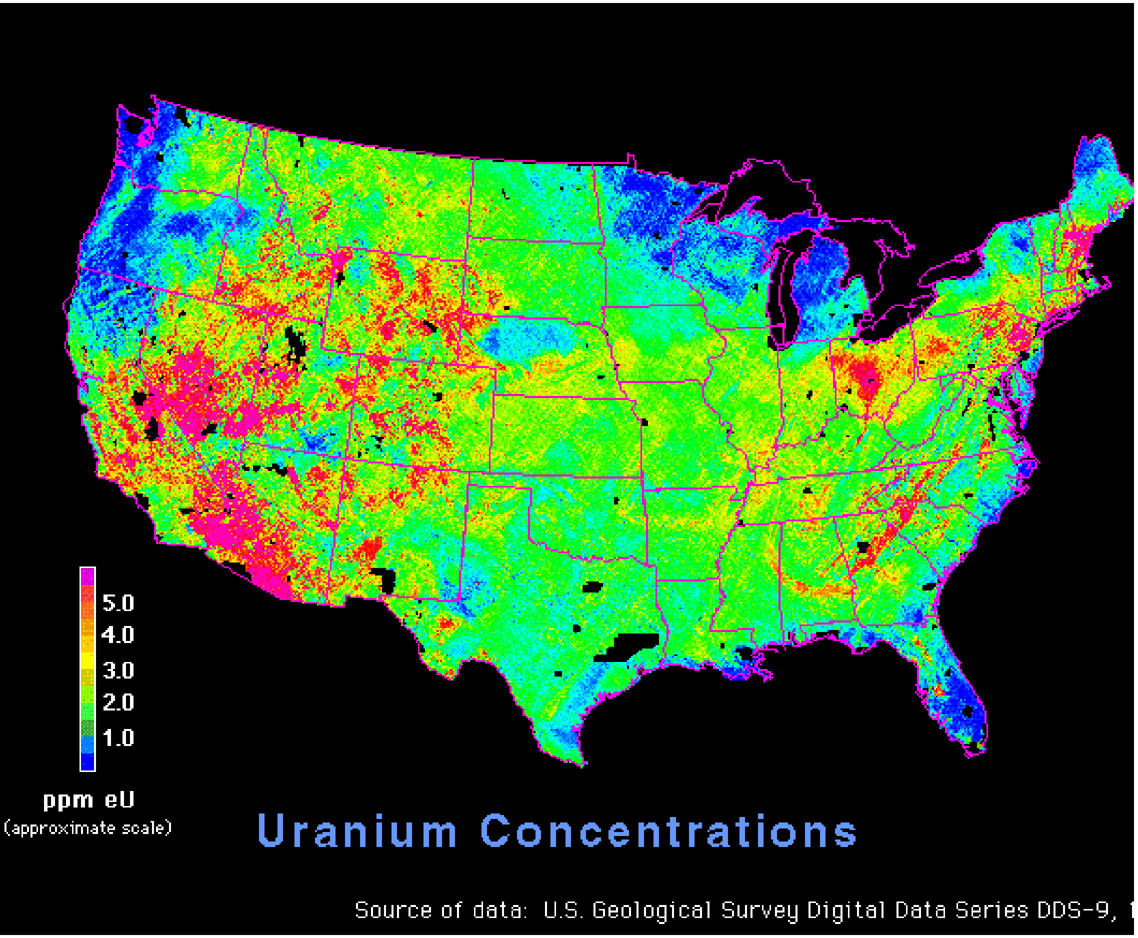




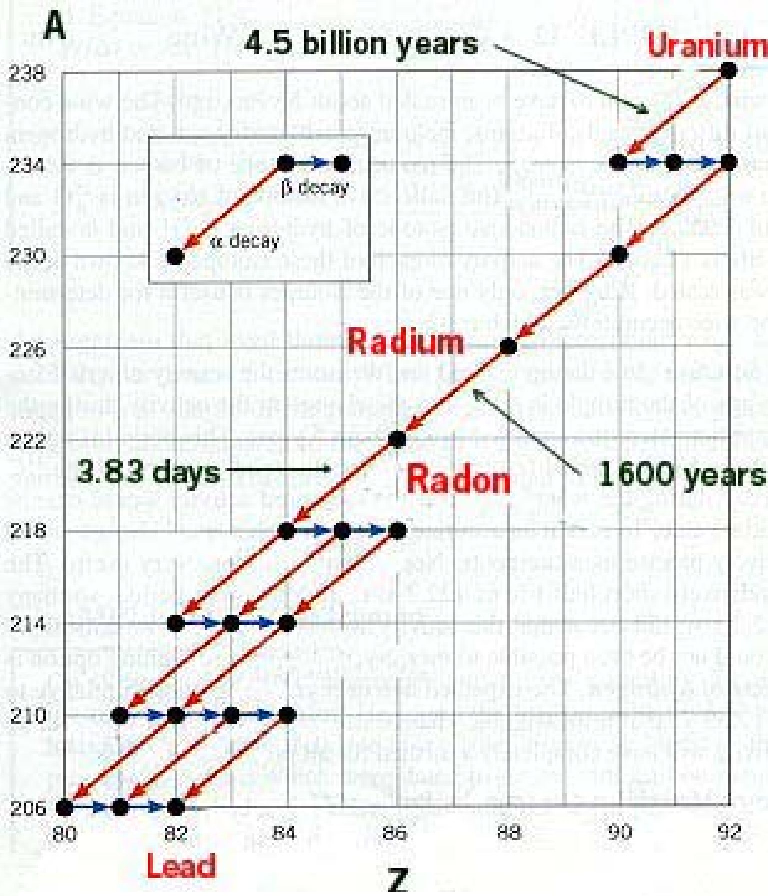
Husband's ring with transatlantic high altitude dose

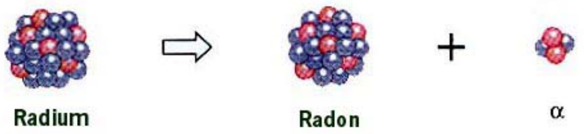
⇨ **8 times more dose**

Natural Radioactivity in the US



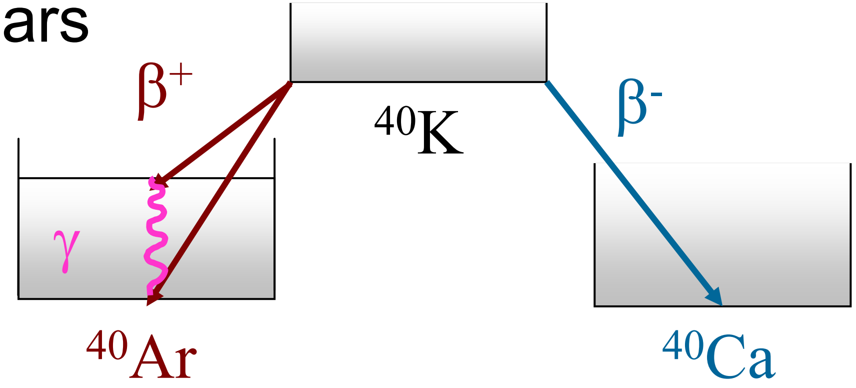
Source of data: U.S. Geological Survey Digital Data Series DDS-9,

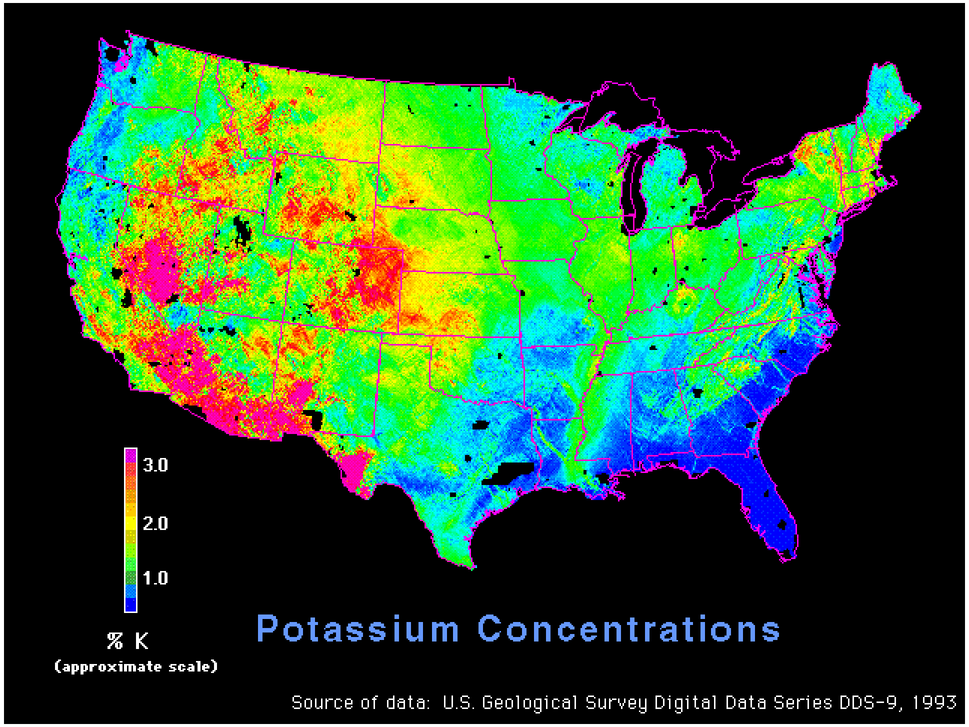




Long lived ^{40}K Radioactivity

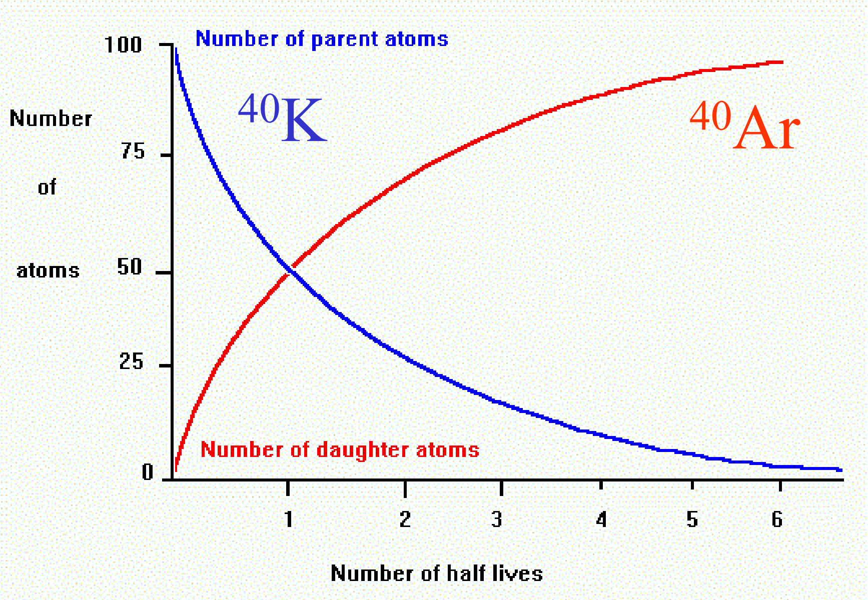
^{40}K has a half-life of $T_{1/2}$=1.28·10^9 years
its natural abundance is 0.021 %





Source of data: U.S. Geological Survey Digital Data Series DDS-9, 1993

Potassium decay to Argon



Internal γ Glowing

On average, 0.27% of the mass of the human body is potassium K of which 0.021% is radioactive ^{40}K with a half-life of $T_{1/2}=1.25\cdot10^9$ [y]. Each decay releases an average of E_{avg}= 0.5 MeV β- and γ-radiation, which is mostly absorbed by the body but a small fraction escapes the body.

Calculate, how many radioactive ^{40}K atoms are in your body system!

Some Mass and Number Considerations

$*$ mass of the body : m_{body}

$*$ mass of potassium K in the body : $m_K = 0.0027 \cdot m_{body}$

$*$ mass of radioactive ^{40}K in the body : $m_{^{40}K} = 0.00021 \cdot m_K = 5.67 \cdot 10^{-7} \cdot m_{body}$

$$40g \text{ of } {}^{40}K \equiv 6.023 \cdot 10^{23} \ atoms$$

$$m_{^{40}K} = 5.67 \cdot 10^{-7} \cdot m_{body} [g] \equiv \frac{6.023 \cdot 10^{23} \cdot 5.67 \cdot 10^{-7} \cdot m_{body}}{40} [particles] = N_{^{40}K}$$

$$\frac{N_{^{40}K}}{m_{body}} = 8.54 \cdot 10^{15} \ [particles / g]$$

to calculate $N_{^{40}K}$, you need the body mass m_{body} in gramm.

for 80 kg body : $N_{^{40}K} = 6.83 \cdot 10^{20} \ [particles]$

Example: ^{40}K

Calculate the absorbed body dose over an average human lifetime of *t* = 70 y for this source of internal exposure.

$$* \quad Dose: \quad D = \frac{E_{absorbed}}{m_{body}} = t \cdot A(^{40}K) \cdot \frac{E_{avg}}{m_{body}}$$

$$* \quad Activity: \quad A(^{40}K) = \lambda \cdot N_{^{40}K} = \ln 2 / T_{1/2} \cdot N_{^{40}K}$$

$$D = 70\,[y] \cdot \frac{\ln 2}{1.25 \cdot 10^{9}\ [\mathrm{y}]} \cdot (8.54\ 10^{15}\ [g^{-1}] \cdot m_{body}) \cdot \frac{0.5\ [MeV]}{m_{body}}$$

$$D = 1.66 \cdot 10^{11} \left[MeV / kg\right] = 2.63 \cdot 10^{-2} \left[J / kg\right] = 2.63 \cdot 10^{-2} \left[Gy\right]$$

$$with: \quad 1\left[eV\right] = 1.602 \cdot 10^{-19} \left[J\right]$$

Prompt Release of Radiation

Nuclear bomb causes sudden release of a high flux on:

γ-rays	$E=h\nu\approx1\text{-}10$ MeV electromagnetic waves
x-rays	$E=h\nu\approx1\text{-}100$ keV electromagnetic waves
α-radiation	^{4}He nuclei
β-radiation	electrons and positrons
neutrons	neutrons
heavy radioactive species (cause for delayed radiation)	

The prompt radiation is absorbed in the surrounding Atmosphere according to exponential absorption law

$$I(d) = I_0 \cdot e^{-\mu \cdot d}$$

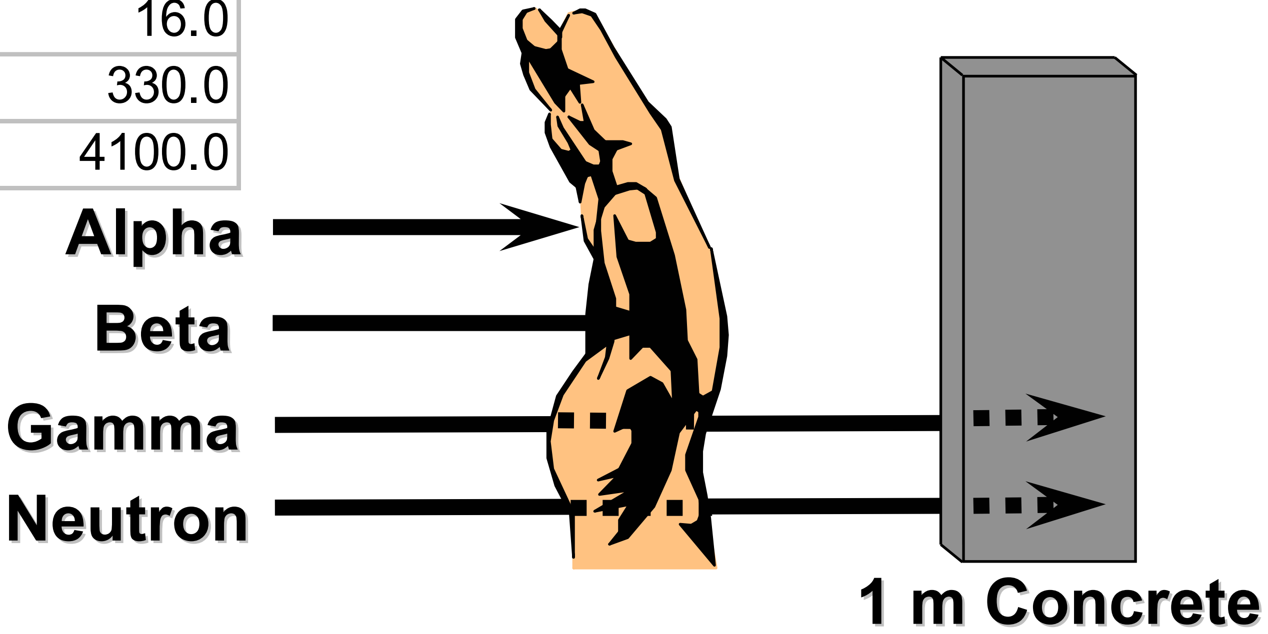
I_0 is the initial intensity and μ is the attenuation coefficient determined by the interaction probability of radiation with molecules and atoms in air.

Absorption probability

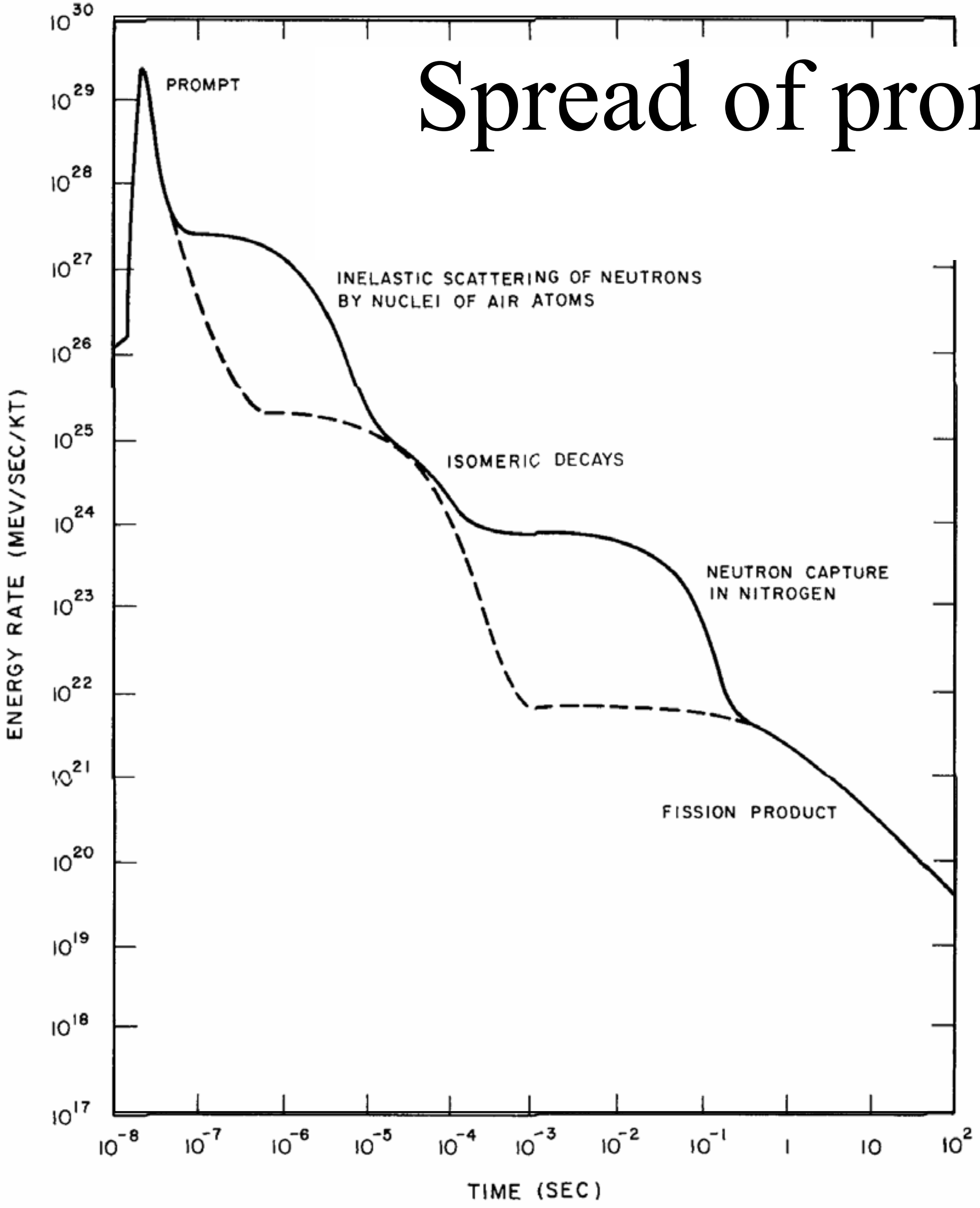
Attenuation coefficient μ depends on energy and nature of particle, medium and interaction probability. High Coulomb scattering probability for charged particles, causes high absorption probability, results in short range!

Energy	Range(α)	Range(β)
keV	cm	cm
10	0.01	0.2
100	0.10	16.0
1000	0.50	330.0
10000	10.50	4100.0

Main component gammas & neutrons



Spread of prompt & secondary γ-radiation



Calculated time dependence of the gamma-ray energy output per kiloton energy yield from a hypothetical nuclear explosion. The dashed line refers to an explosion at very high altitude.

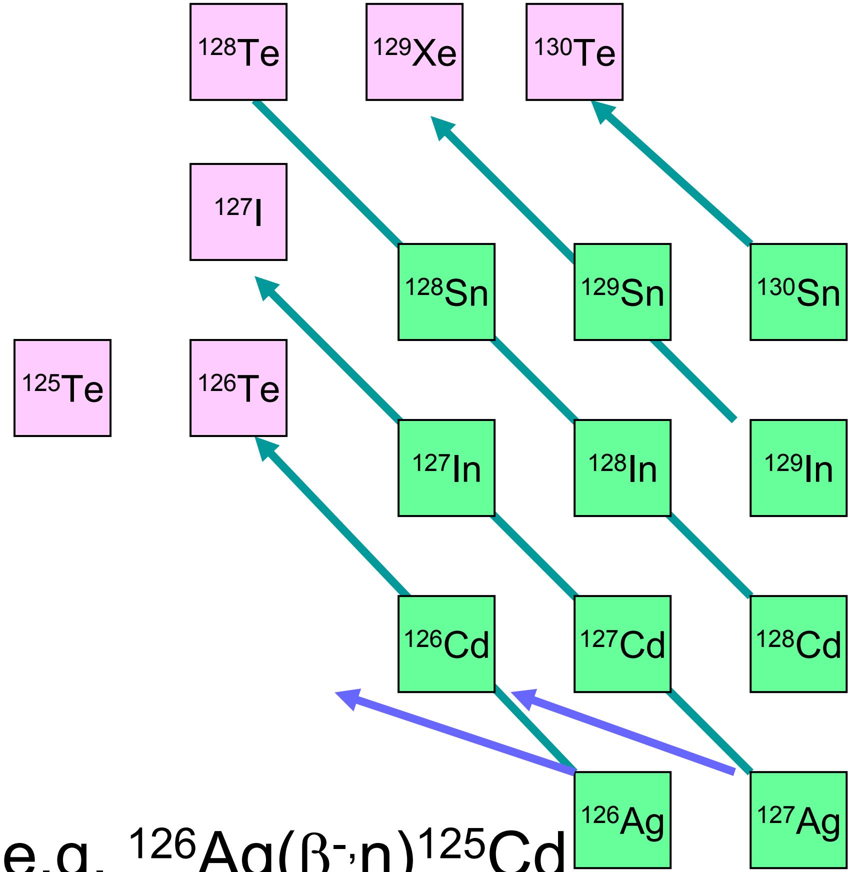
Neutrons originated secondary γ radiation by inelastic neutron scattering as well as by neutron capture on nitrogen isotopes in the surrounding air. Secondary γ-production enhances radiation flux and radiation extension.

Fission products

Production of neutron-rich radioactive isotopes in the mass 80-130 range which decay by β^- decay or by β-delayed neutron emission

Back to stable isotopes.

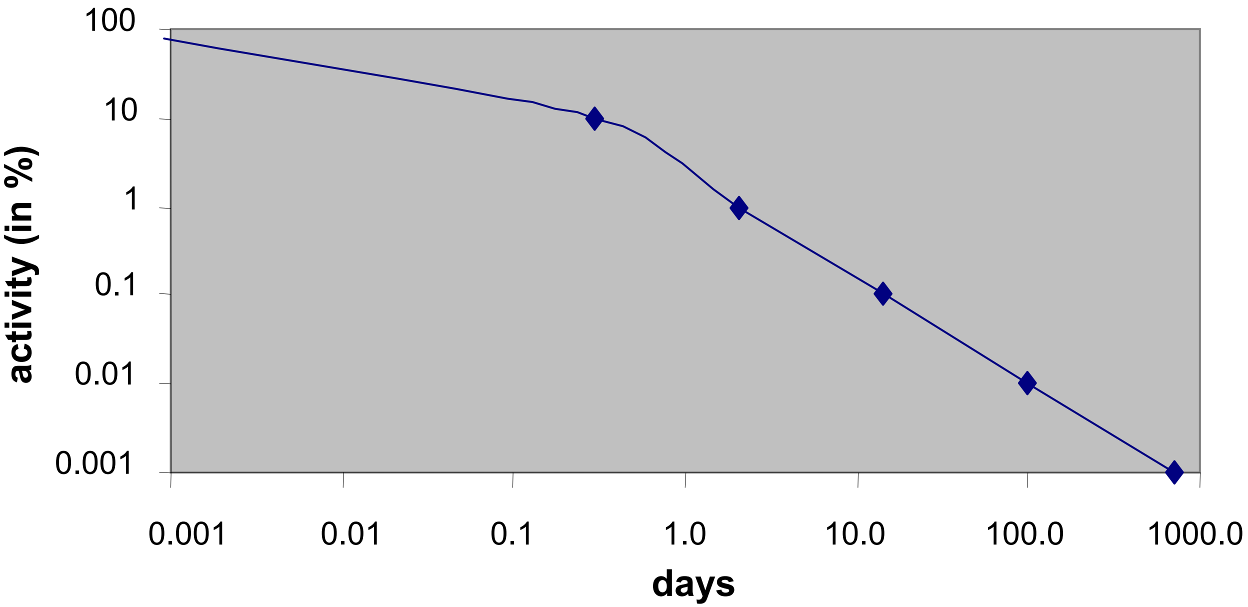
Decay time scale depends On the associated half-lives which determine the flux and time scale for delayed radiation exposure.



e.g. $^{126}Ag(\beta^{-},n)^{125}Cd$
vs $^{126}Ag(\beta^{-})^{126}Cd$

Decline by the “rule of seven”

This rule states that for every seven-fold increase in time following a fission detonation (starting at or after 1 hour), the radiation intensity decreases by a factor of 10. Thus after 7 hours, the residual fission radioactivity declines 90%, to one-tenth its level of 1 hour. After 7·7 hours (49 hours, approx. 2 days), the level drops again by 90%. After 7·2 days (2 weeks) it drops a further 90%; and so on for 14 weeks.



The rule is accurate to 25% for the first two weeks, and is accurate to a factor of two for the first six months. After 6 months, the rate of decline becomes much more rapid.

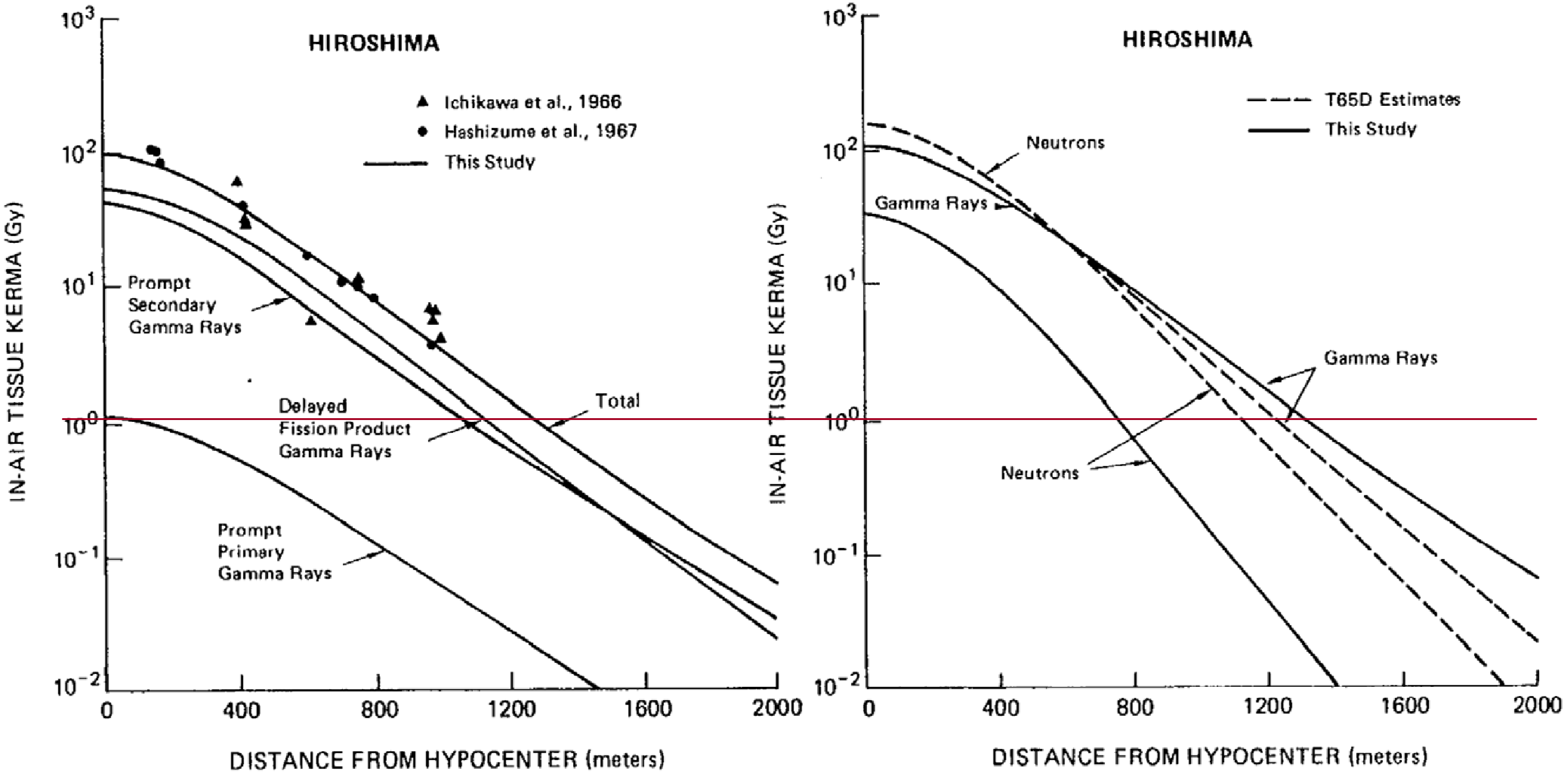
Studies of impact of ionizing radiation on the human body - Hiroshima -

US-Japanese teams medical tests, autopsies, human organ analysis, on-site radioactivity measurements …

autopsy

Hiroshima radiation spread data

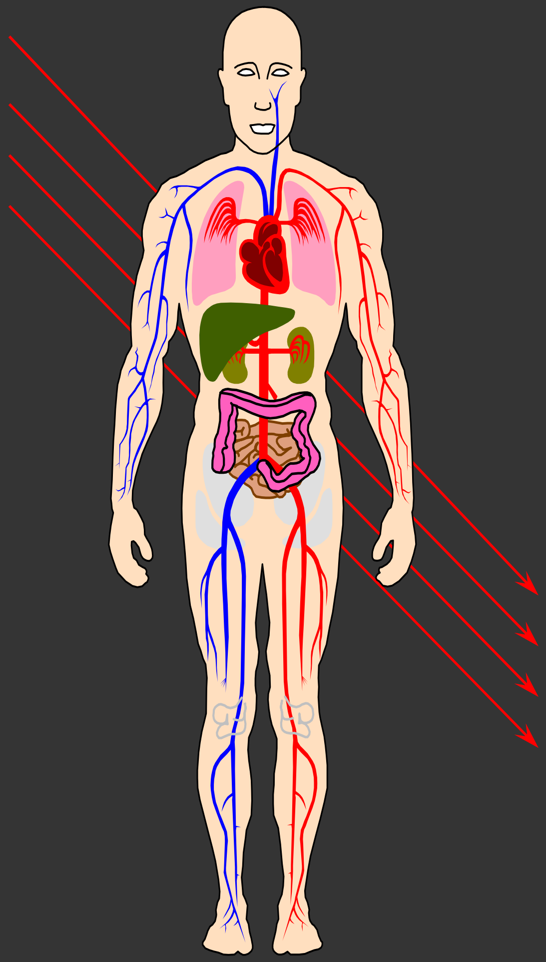
Primary γ ray originated low dose of <100 rad near the hypocenter, secondary γ-ray originated dose of >100 rad within 1500 m radius



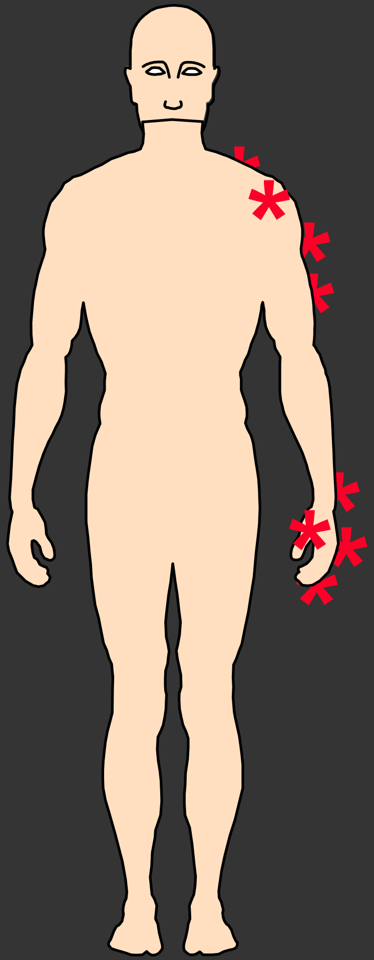
Kerma versus distance for the various components of the radiation in Hiroshima (data from Kerr et al.[10]). doses are in grays (1 Gy = 100 rad).

Radiation Exposure Types

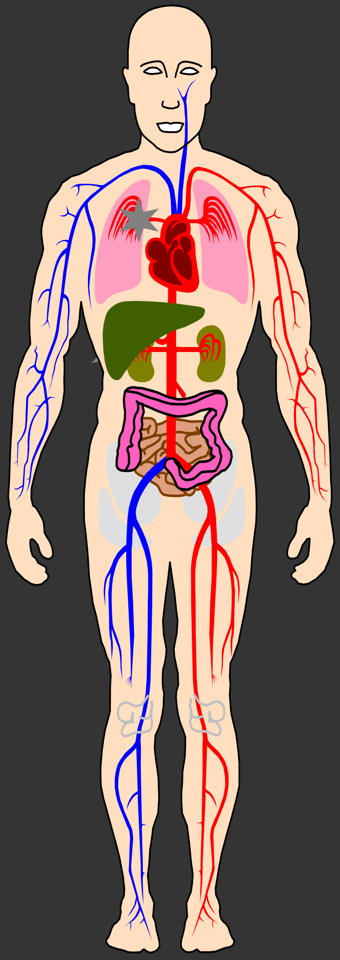
Irradiation



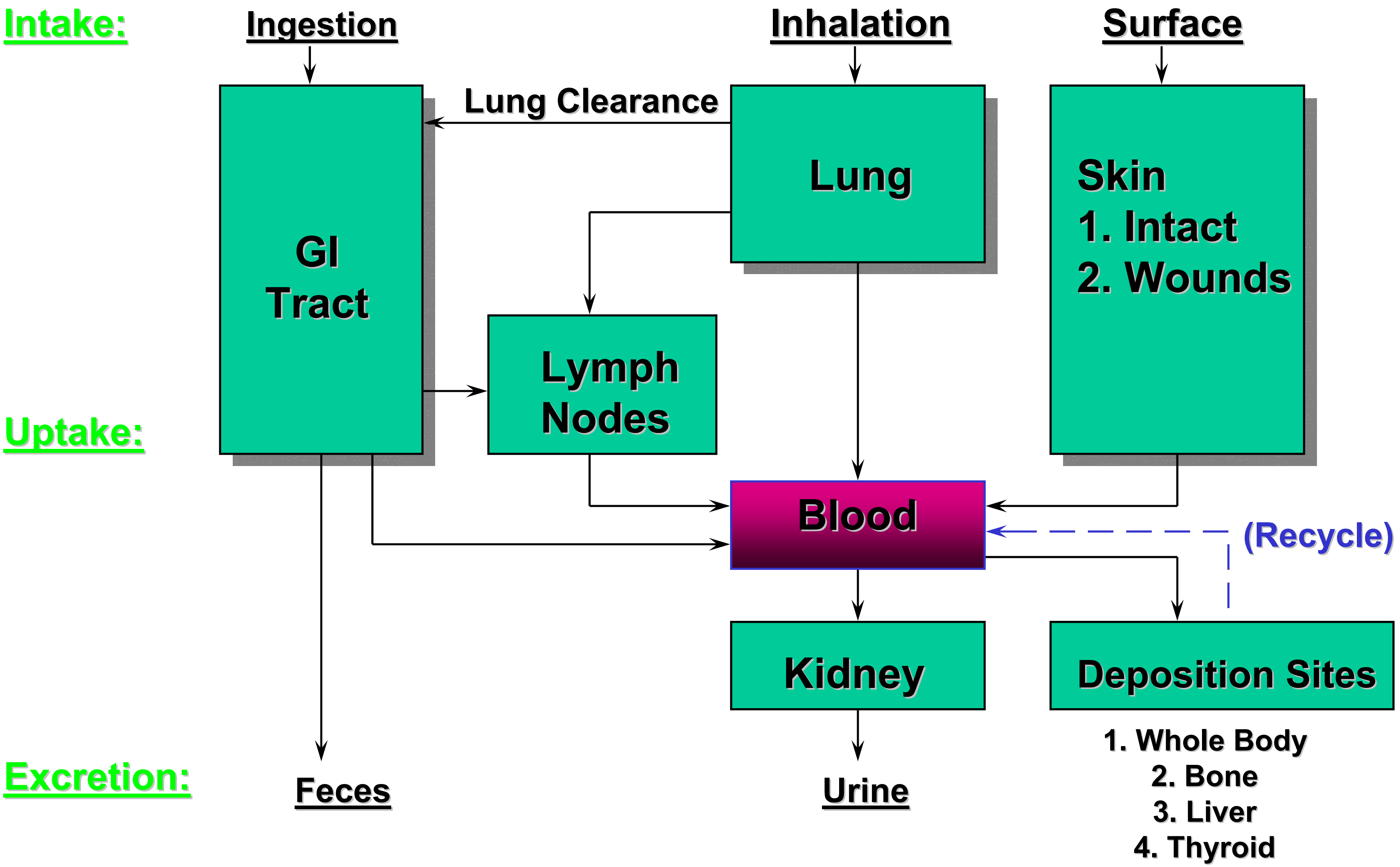
External Contamination



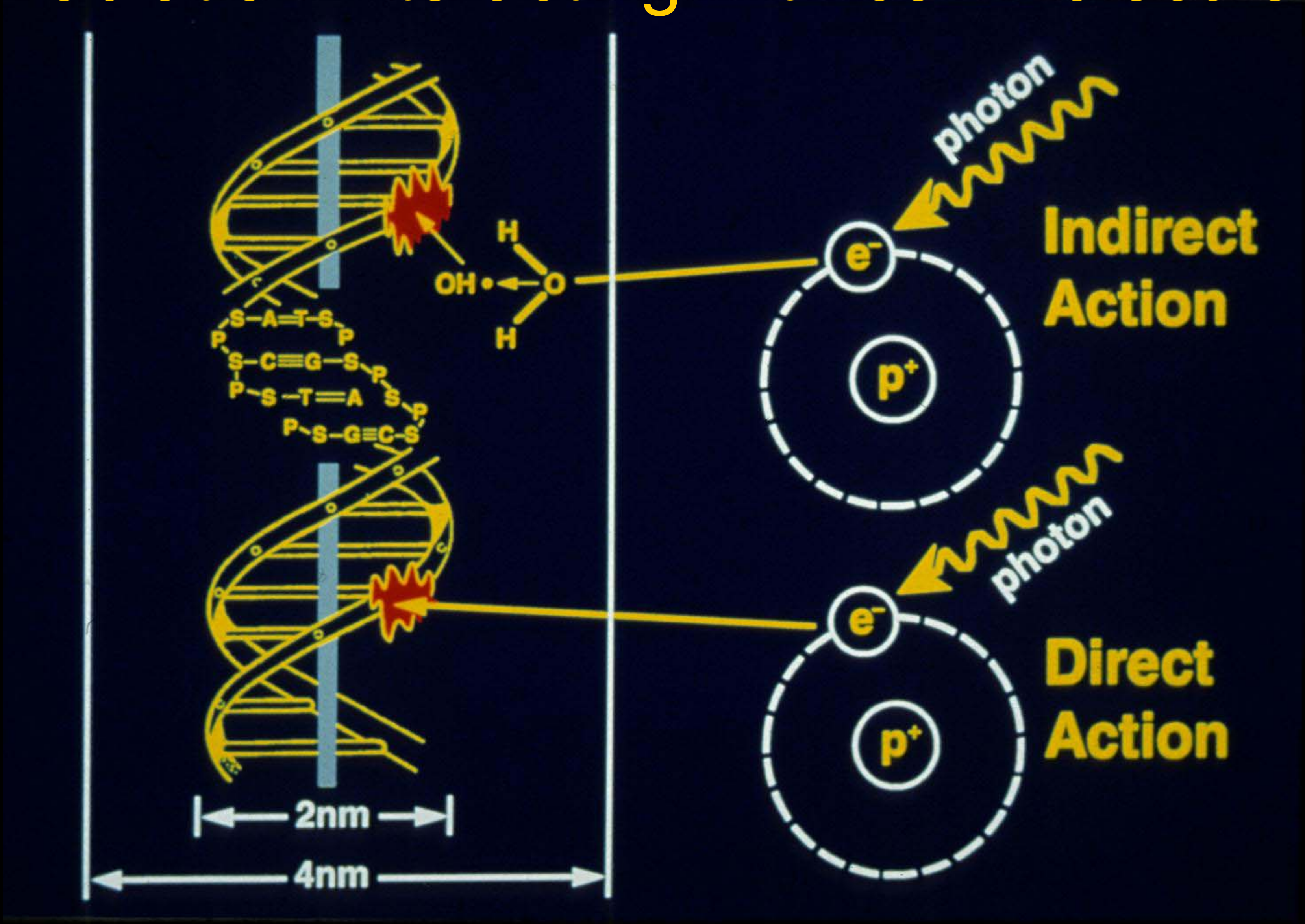
Internal Contamination



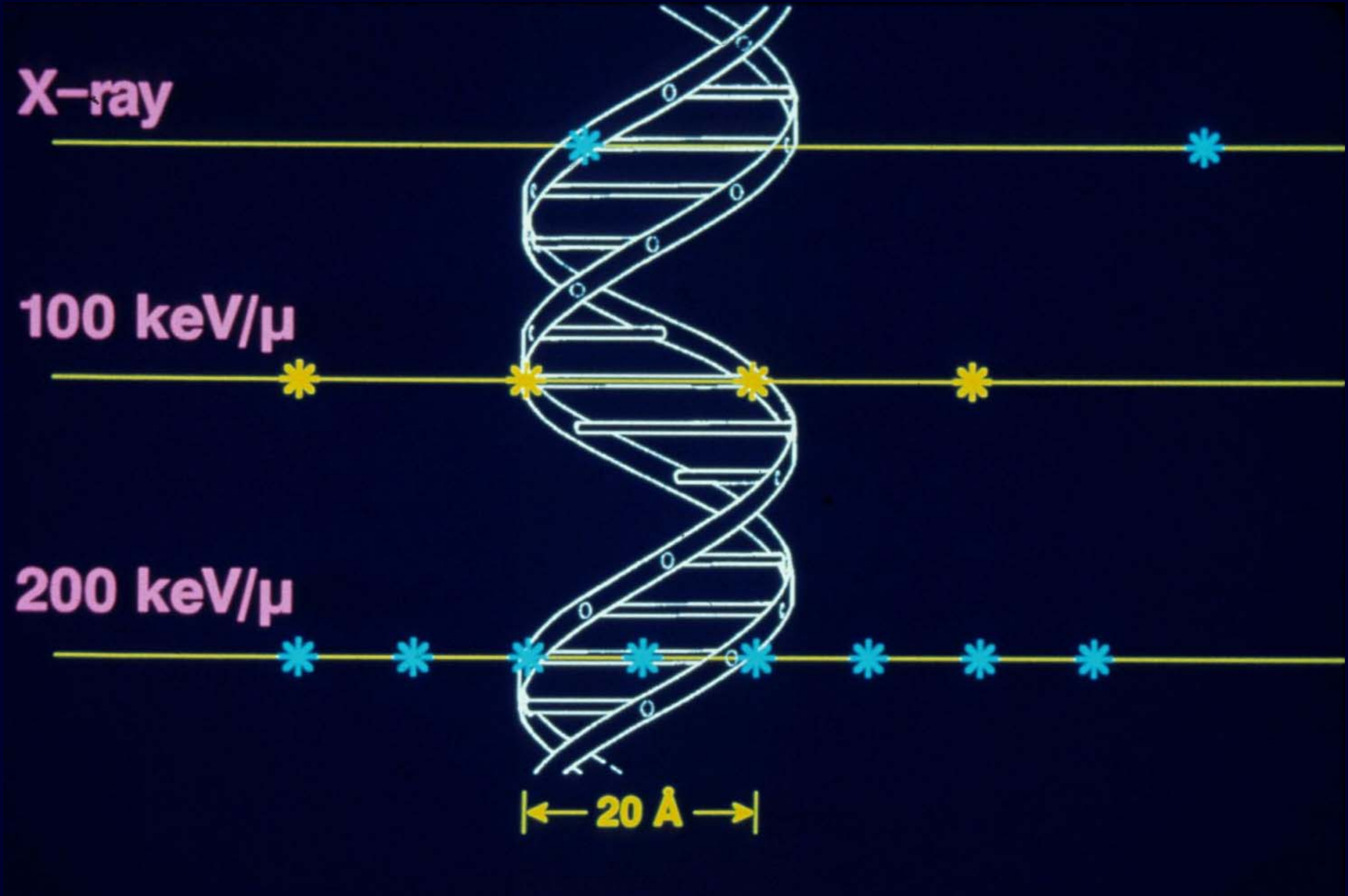
Schematic Model of Radionuclide Uptake



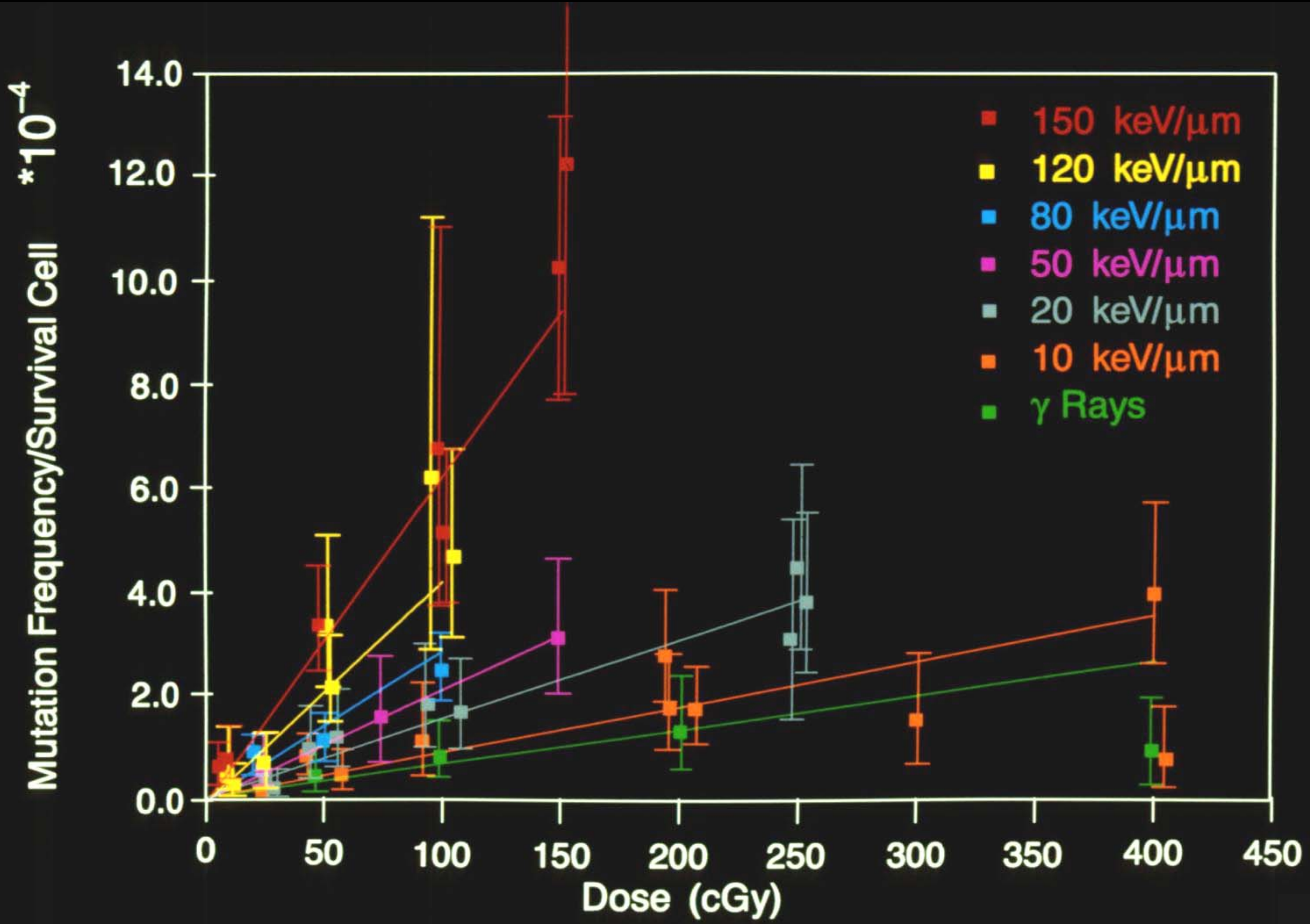
Radiation interacting with cell molecules



Energy dependence of radiation damage

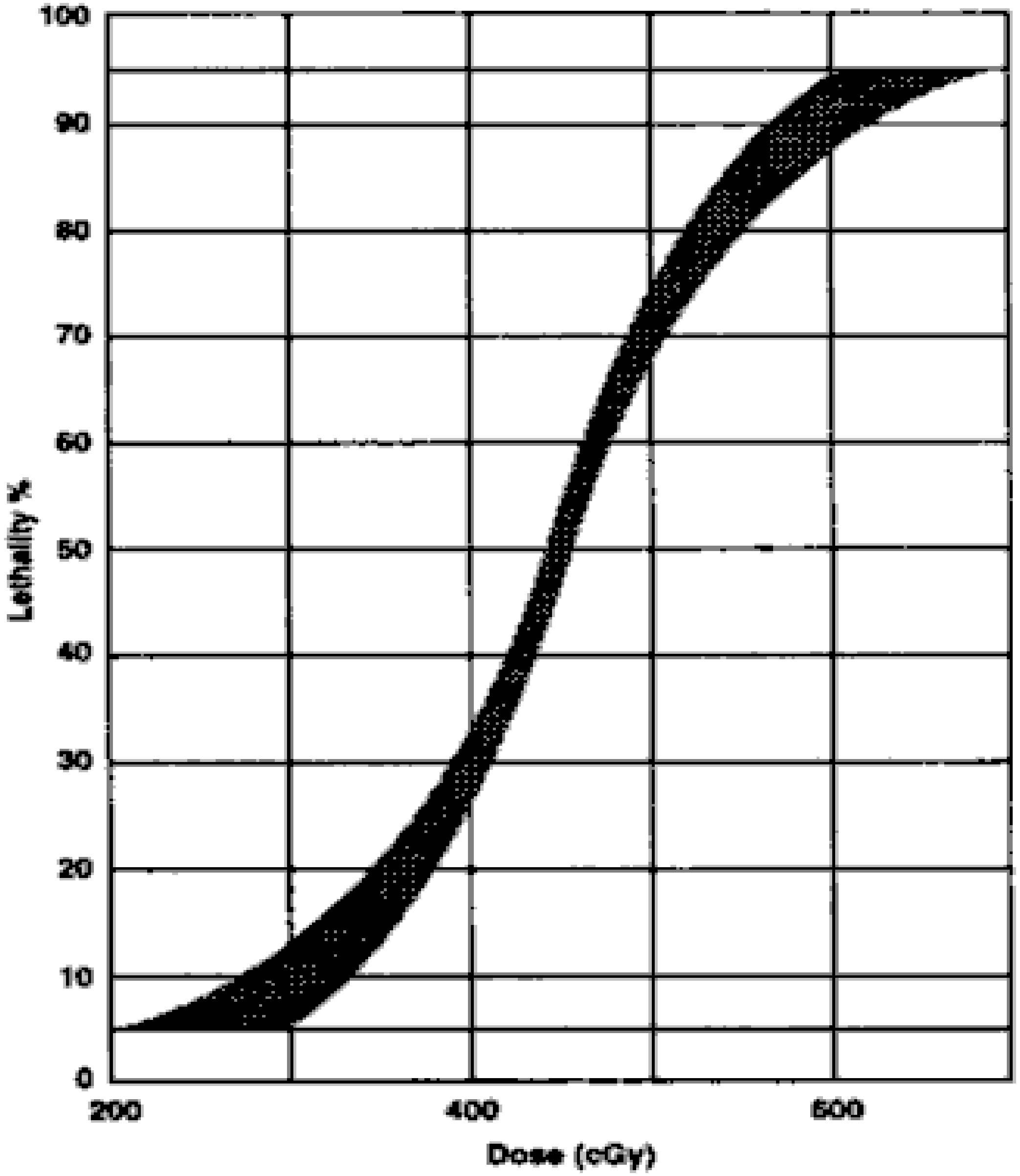


Linear energy transfer (LET): amount of energy deposited per unit track length

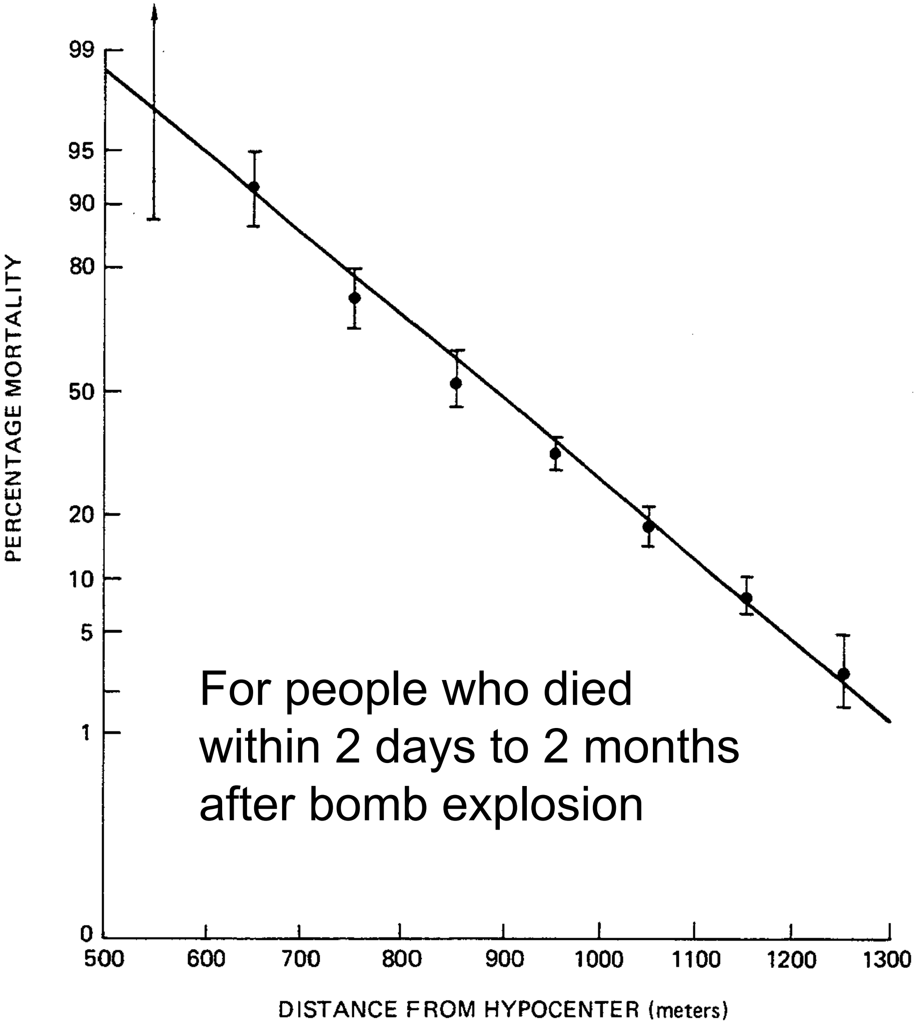

Mutation Frequency/Survival Cell *10^-4
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
0
50
100
150
200
250
300
350
400
450
Dose (cGy)
■ 150 keV/µm
■ 120 keV/µm
■ 80 keV/µm
■ 50 keV/µm
■ 20 keV/µm
■ 10 keV/µm
■ γ Rays

Human lethality as function of Dose

A 50% lethality
is reached at
an accumulated
dose of 450 cGy
=450 rad=4.5 Gy.
A 100 rad dose
is survivable.

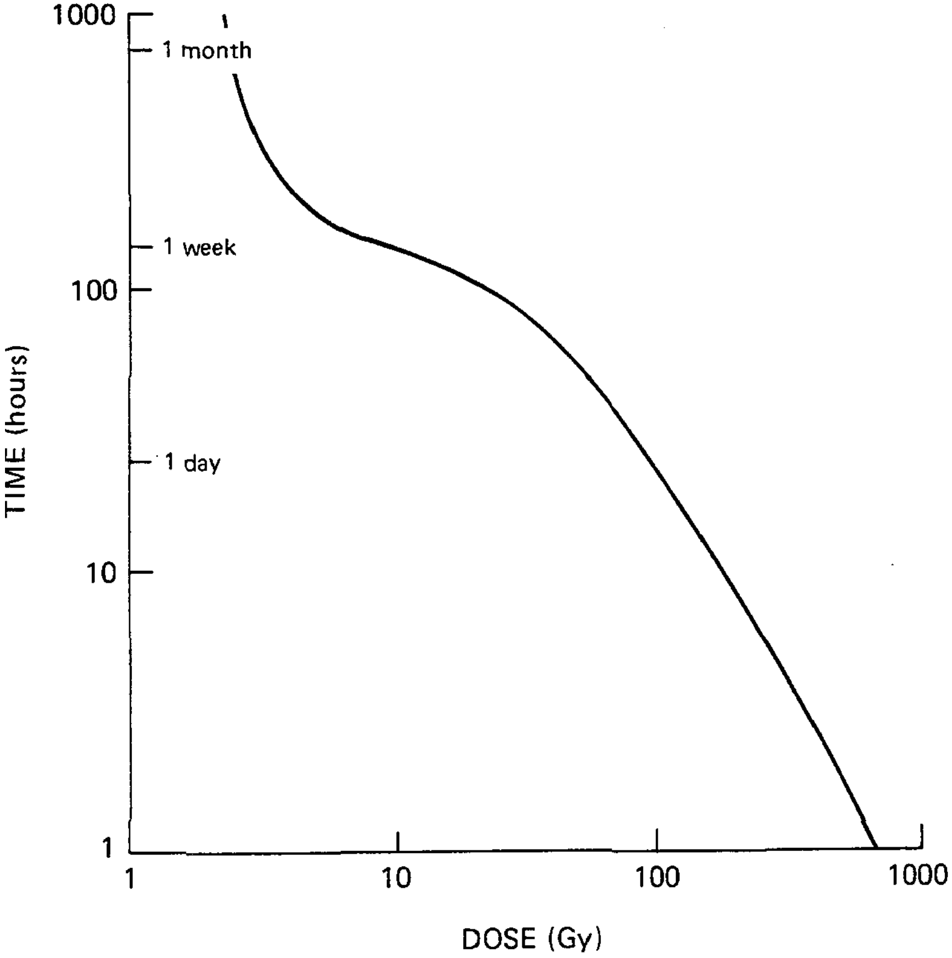


Survival Chance



For people who died within 2 days to 2 months after bomb explosion

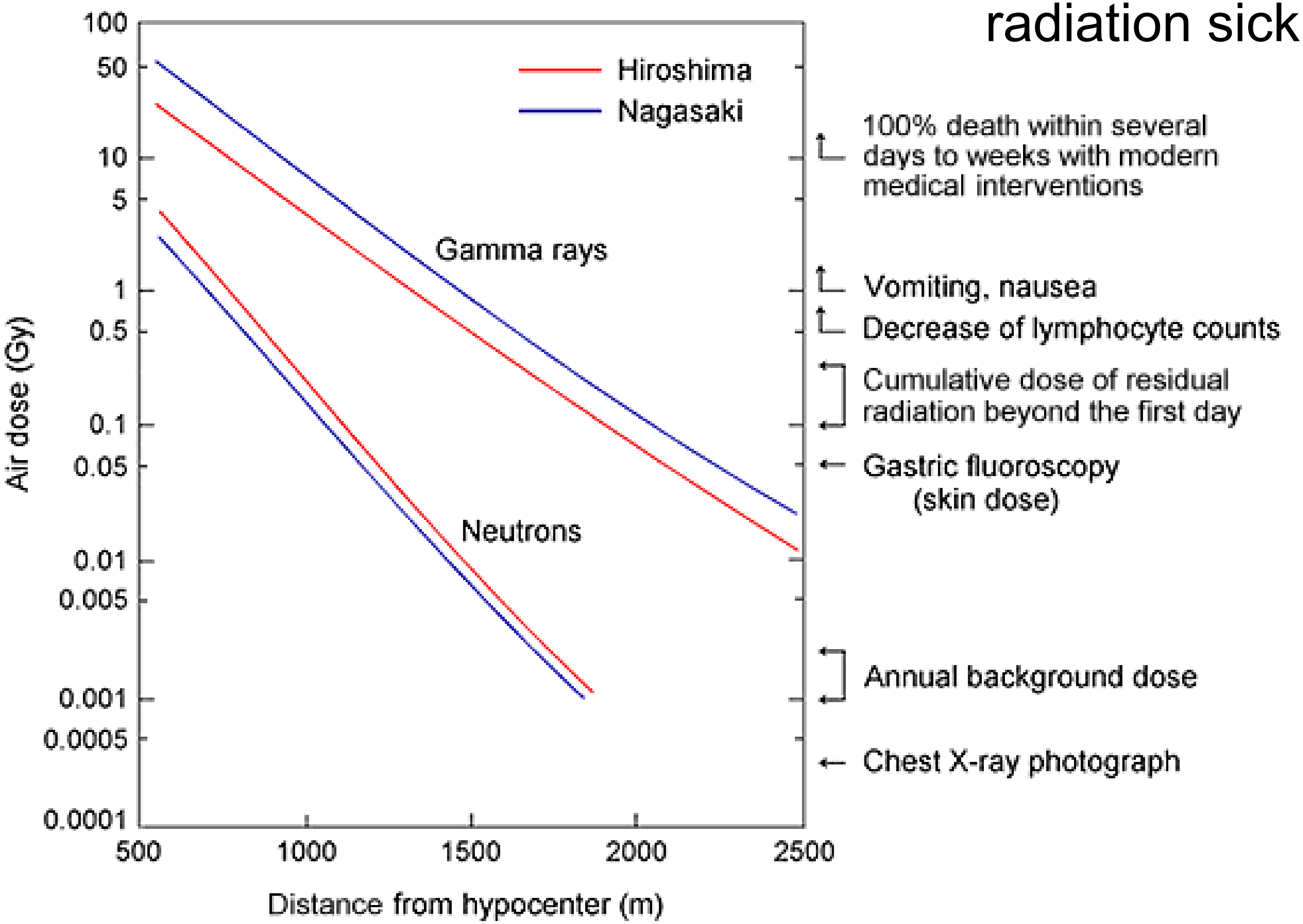
Probability of death as a function of distance from the hypocenter



Time of occurrence of death from acute radiation effects.

Radiation Side Effects

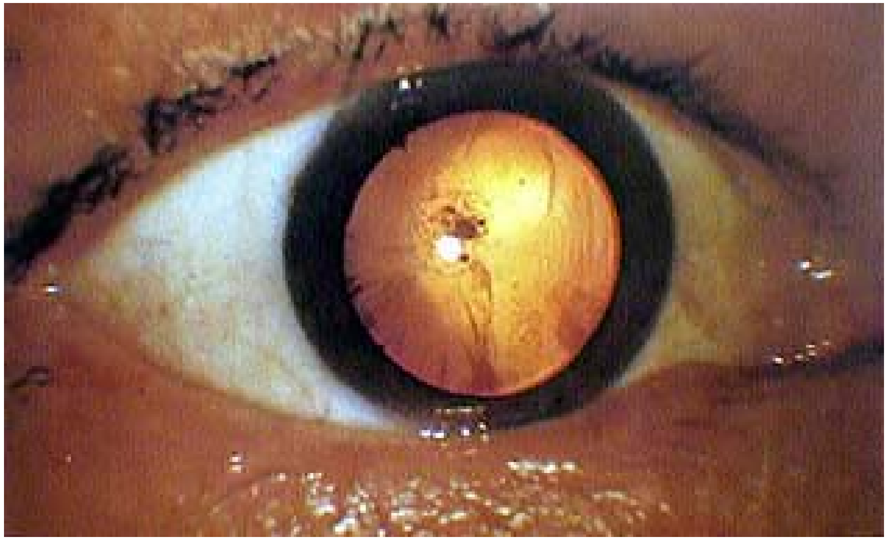
radiation sickness

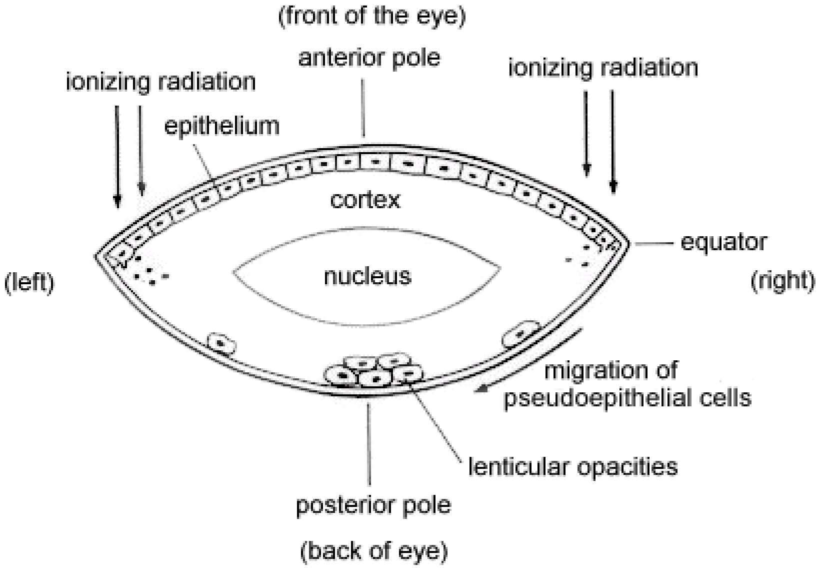


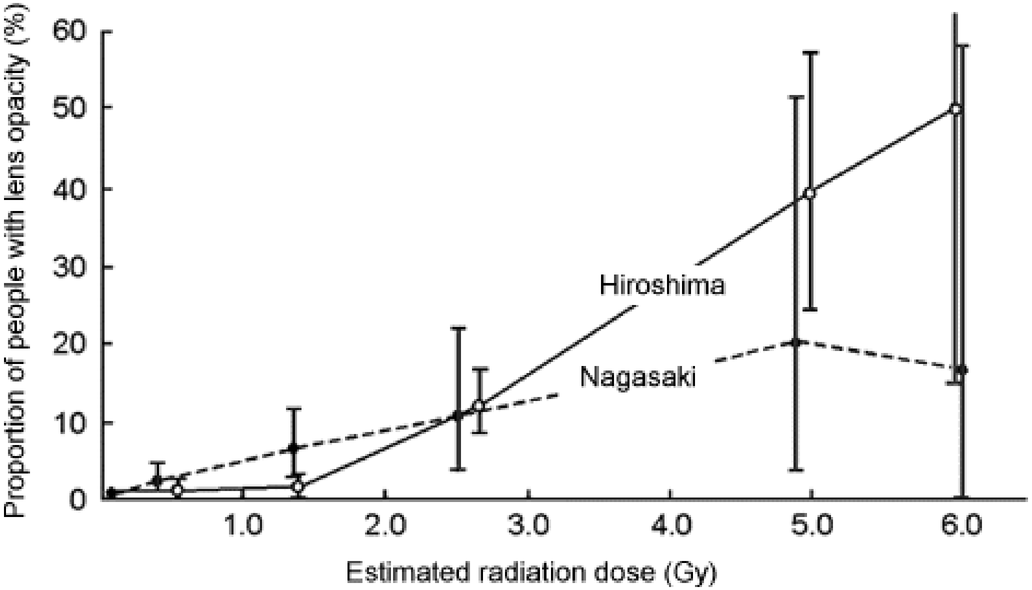
Purpura, Vomiting, …

Purpura, or bleeding under the skin, is one of the symptoms of acute radiation sickness. The heavily exposed survivors experienced fever, nausea, vomiting, lack of appetite, bloody diarrhea, epilation, purpura, sores in their throat or mouth (nasopharyngeal ulcers), and decay and ulceration of the gums about the teeth (necrotic gingivitis). The time of onset of these symptoms depends on the exposure level.

Long term effects - blindness



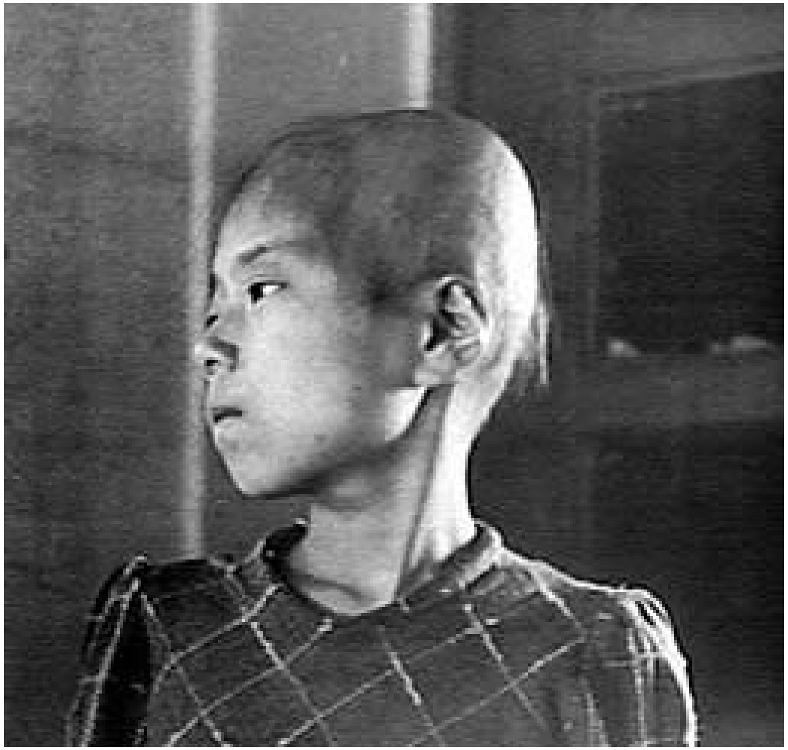




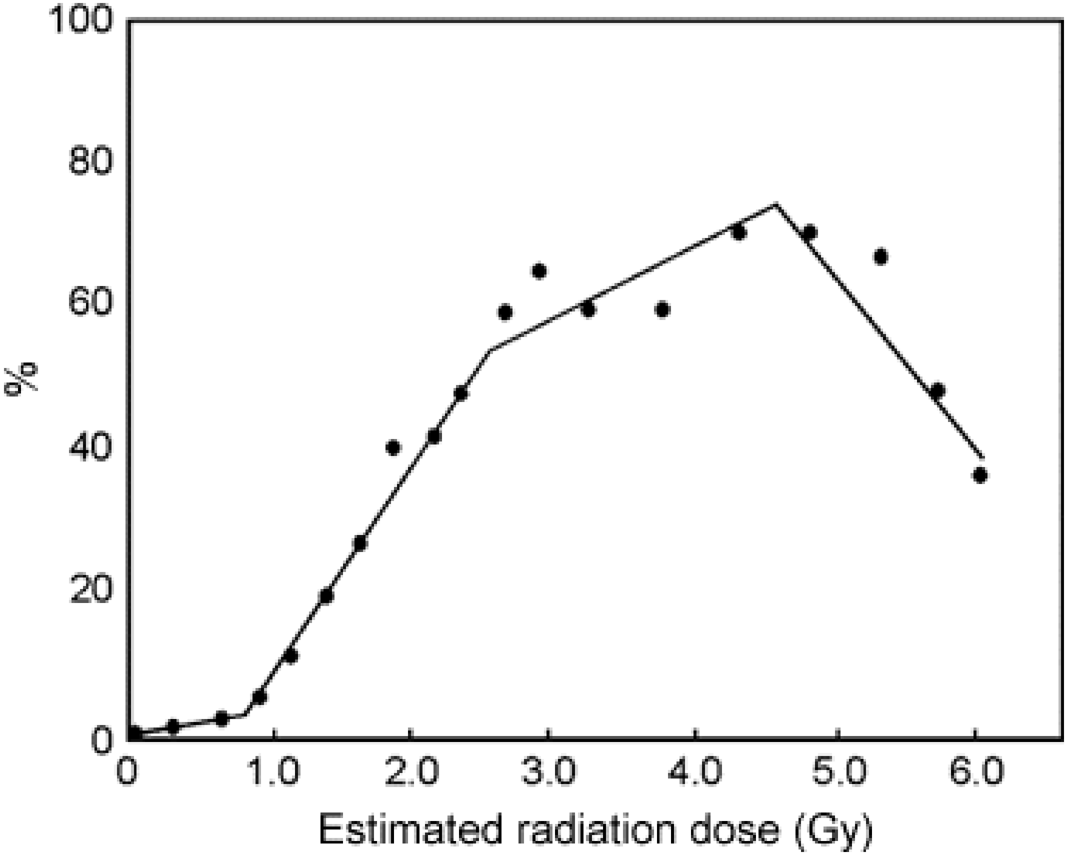
Radiation damage to epithelial Cells. Damaged cells move to the back of the eye and cause lens opacity by blocking light. Occurs with 50% chance for people with dose of ~500 rad.

Epilation – severe loss of hair

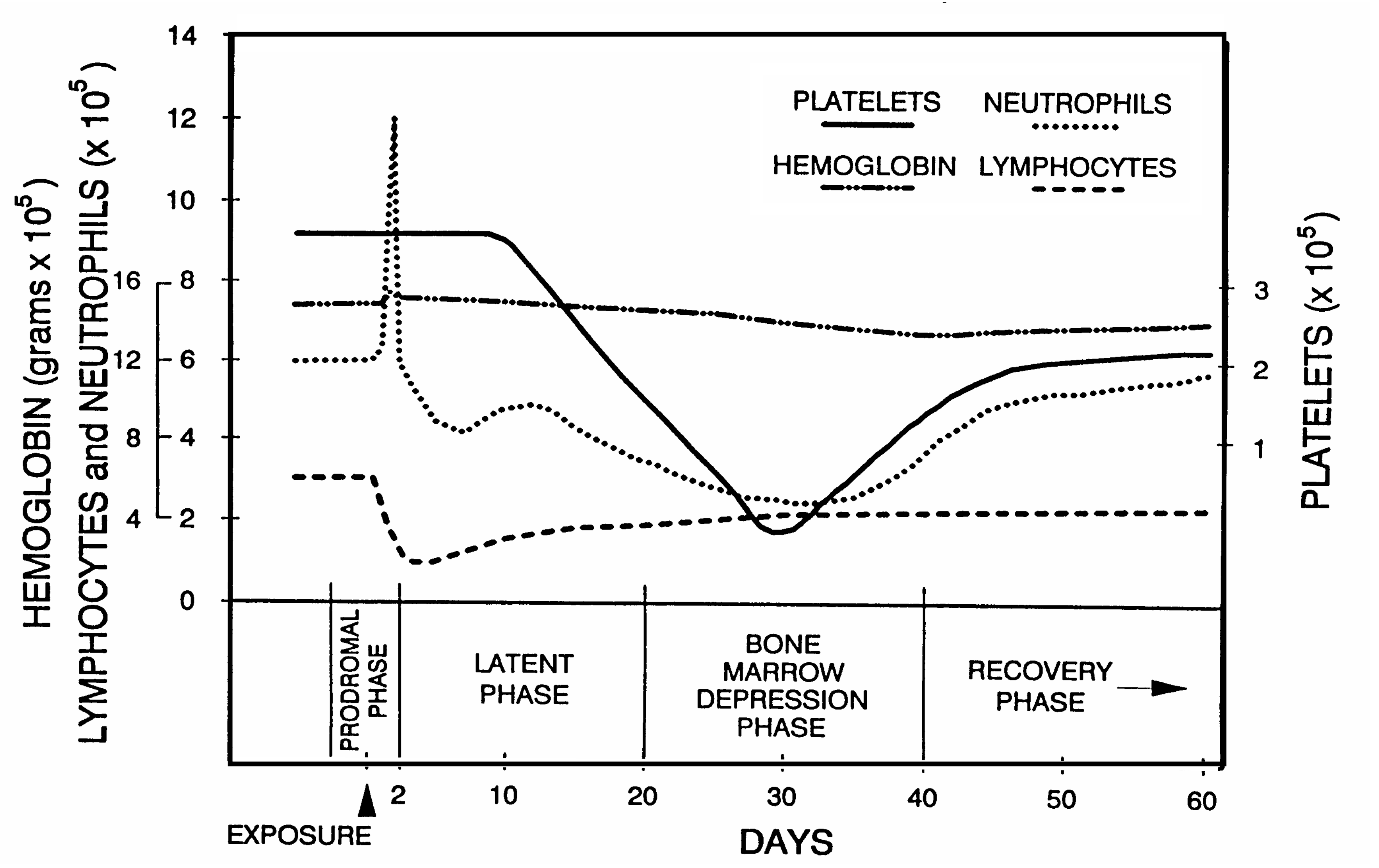
Hair loss is a common sign of radiation exposure & sickness.
Severe epilation (2/3 hair loss) occurs at doses of >200 rad.



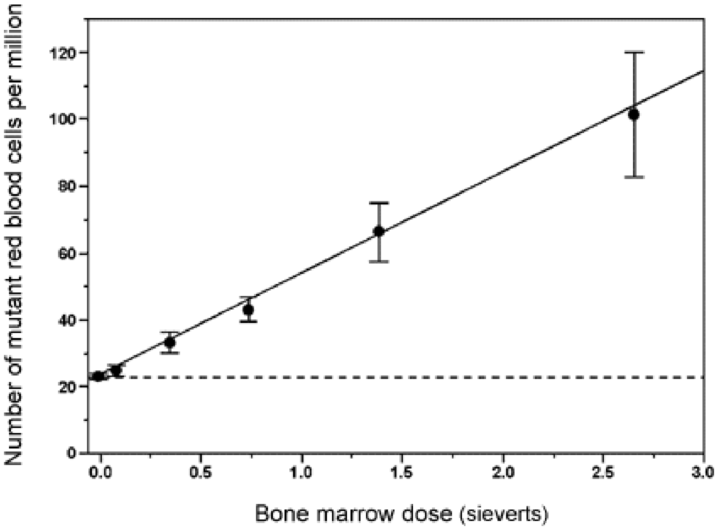
2km from hypocenter



Hemogram
blood impact of 300 rad exposure

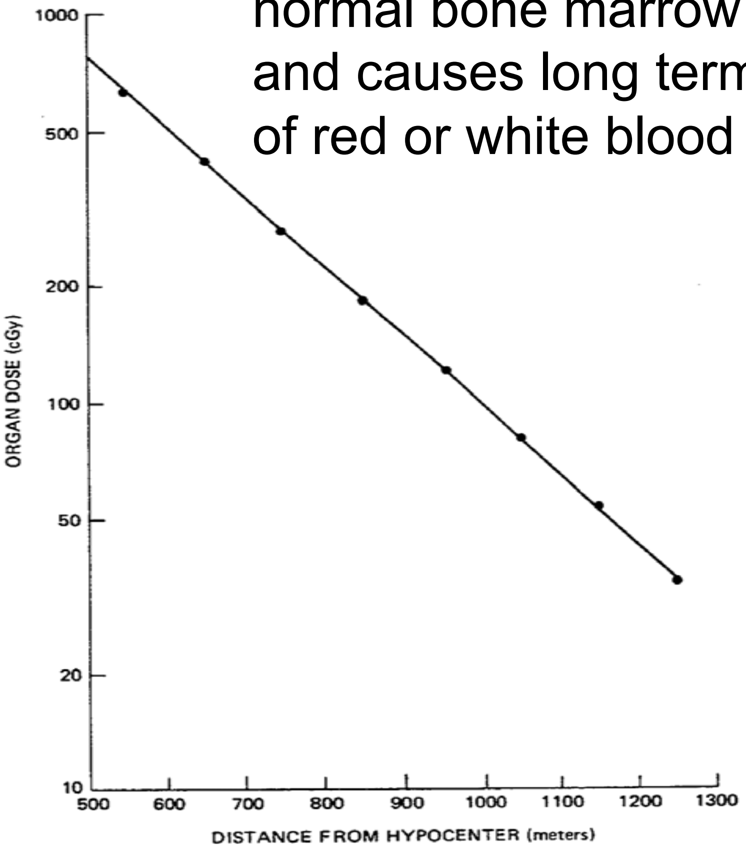


Radiation impact on bone marrow

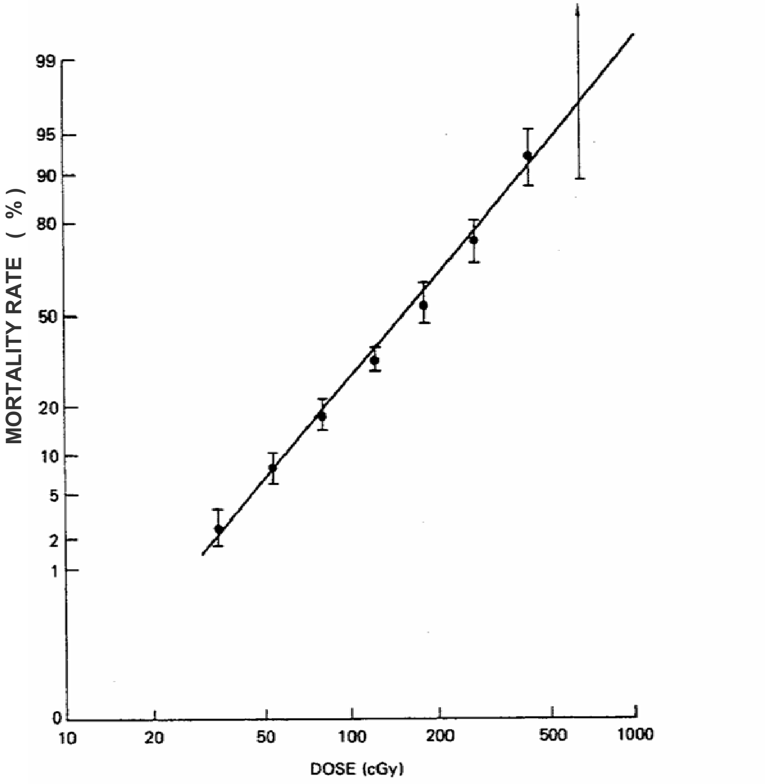


100 rad = 1 Gy ≈ 1 Sv

Radiation >2 Gy suppresses normal bone marrow functions and causes long term mutation of red or white blood cells



Bone marrow dose versus distance from hypocenter in the Hiroshima survey group.

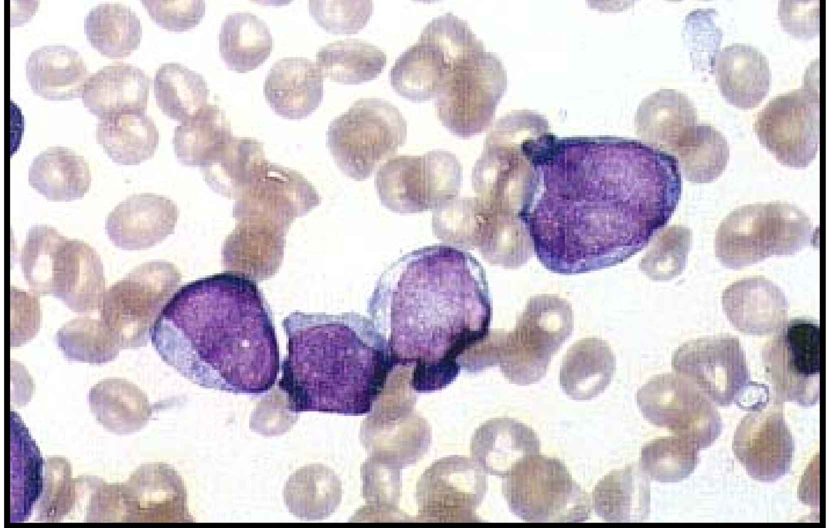


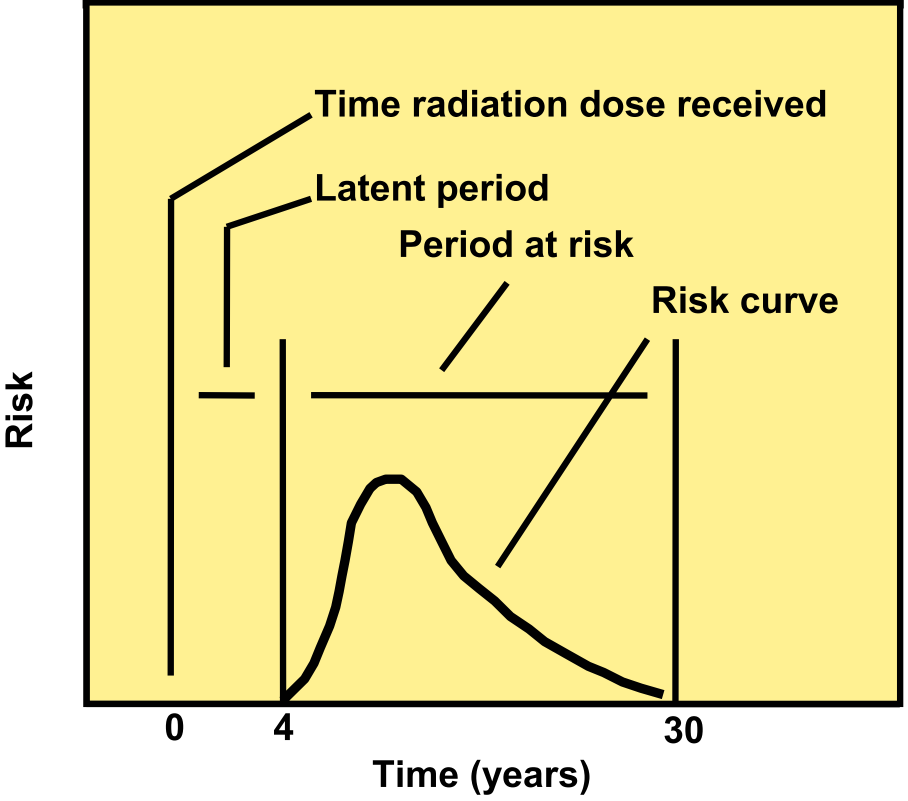
Percent mortality versus bone marrow dose in the Hiroshima survey

Leukemia

When leukemia develops, the body produces large numbers of abnormal blood cells. In most types of leukemia, the abnormal cells are white blood cells.

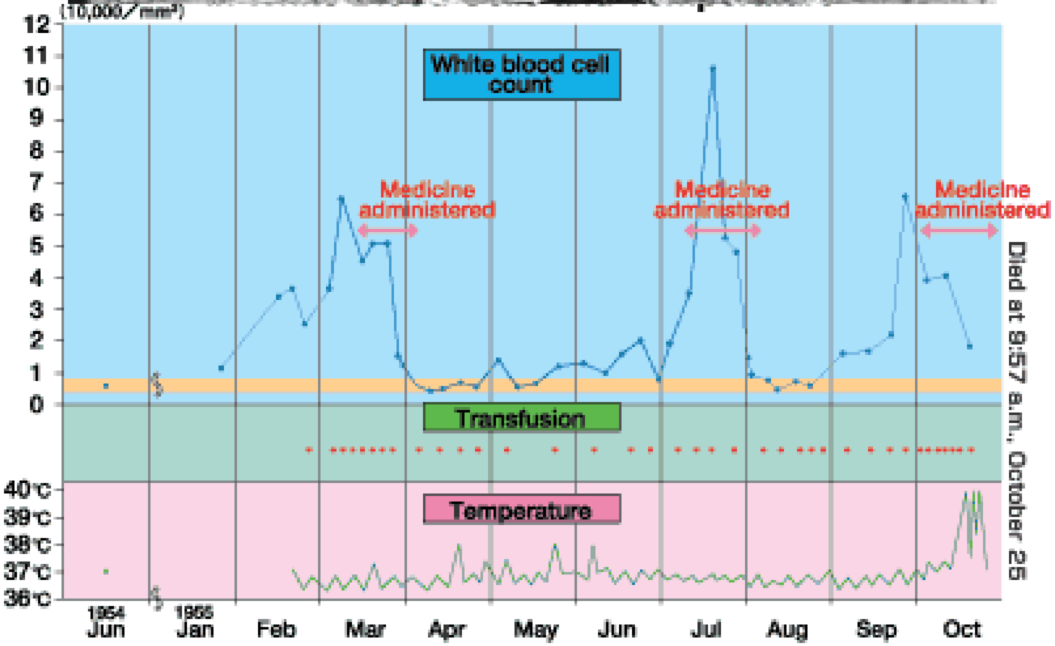
An increase in the number of leukemia cases was first noted in the late 1940s. As of 1990, there were 176 leukemia deaths among 50,113 survivors with significant exposures (>0.5Gy). It is estimated that about 90 of these deaths are associated with radiation exposure.





Leukemia Latency and Time at Risk Periods

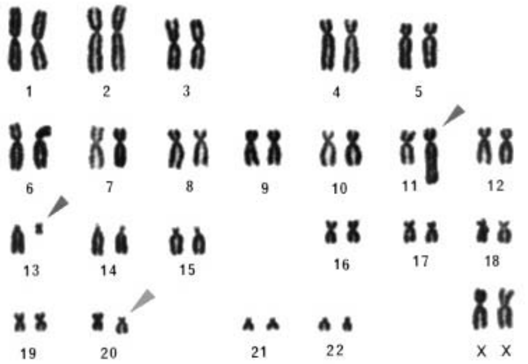
Leukemia – case of Sadako

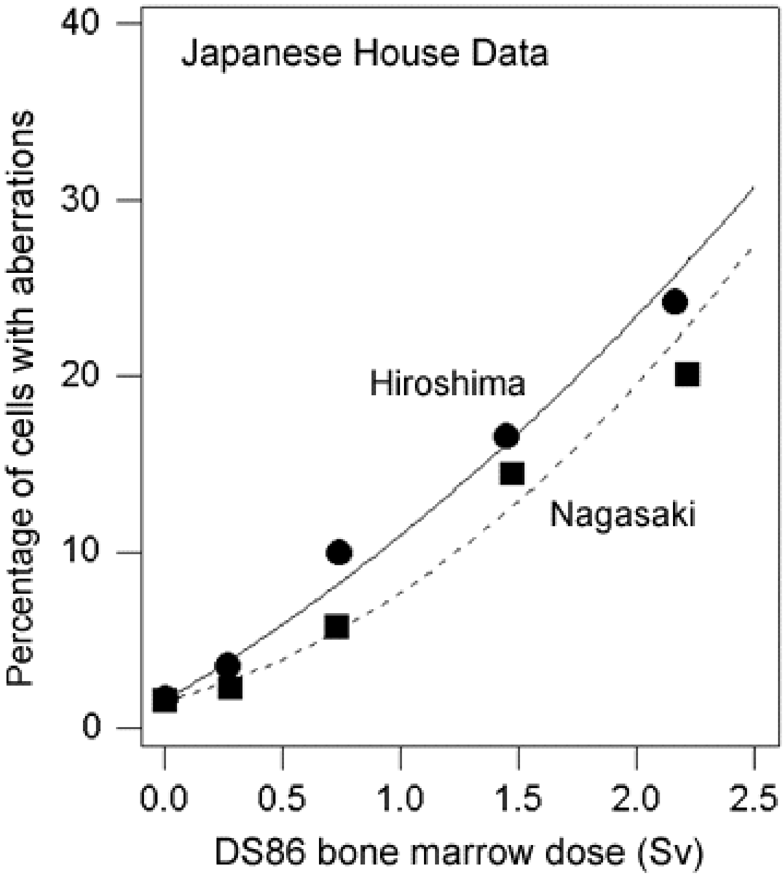


Note) ▨ Standard white blood count 4,000 to 8,000 / mm³
June is the results of Sadako's blood test during a physical exam.

Long range genetic effects

Chromosomes observed during cell division. Abnormal ones are marked by grey arrow.





Observed increase with dose indicates long term genetic effects