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Part 1

Radiation Safety:
Physical Aspect

1. Physical nature and sources of ionizing radiation
2. The composition of the atomic nucleus. Characteristics of the nuclei. Isotopes and isobars. Radioactivity, radioactive radiation. Radioactive decay law. The main patterns of alpha and beta decays, gamma radiation of nuclei. Physical bases of interaction of ionizing radiation with matter: energy transfer, ionization. Linear energy transfer. Interaction of alpha particles with matter. Interaction of beta particles with matter. Passage of gamma quanta through matter. Interaction of neutrons with matter. Principles of registration of charged particles and gamma quanta.
3. Man-made radioactive sources. Sources of beta, alpha, gamma and X-ray radiation; isotopic neutron sources; closed sources; open sources and isotope generators; general principles for the safety of radiation sources; production of radioisotopes
4. Nuclear weapons. Damage factors. Radioactive fallout.
5. Nuclear reactors: a review of nuclear fission and fusion reactions; neutron slowdown; neutrons, multiplication factor, criticality; the main elements of a nuclear reactor; types of reactors; experimental reactors; nuclear fuel cycle facilities. Radiation sources in the reactor core and in the process loop. NPP emissions into the atmosphere. Materials for protection against neutron radiation.
6. Radiation generators. Generation of charged particles: linear accelerators; betatrons; cyclotrons. X-ray generation: low-energy X-ray units; linear accelerators; other units; principles and spectra; filtering and beam quality. Neutron generation: (d, n) and (p, n) reactions; generation of neutrons for neutron therapy. The use of ionizing radiation in medicine, industry, and agriculture.
7. Basics of spaceflight radiation safety. Radiation conditions in outer space. Galactic and solar cosmic rays. Radiation belts of the Earth. Features of radiation protection in space. Space flight radiation safety standards. Ensuring radiation safety in aviation and space flights.
8. Detection of radioactive radiation.
9. Activity and its units of measure. Specific, specific volume and specific surface activity. Basic, normalized and operational quantities of radiation safety. Exposure, absorbed, equivalent, and effective dose of radiation. Dose rate. Individual and collective exposure dose, expected exposure doses. Dosimetric quantities of exposure (power); kerma (power); transferred energy; absorbed dose (power); linear energy transmission (LET); linear energy; dose per organ. Radiation protection quantities. Equivalent dose (power); radiation weighting factor (wR); effective dose; tissue weighting factor (wT); operational quantities: ambient dose equivalent; directional dose equivalent; personal dose equivalent; expected dose.
10. Devices for radiometric and dosimetric control. Gas-filled detectors. Ionization chambers with current measurements; integrating chambers; high pressure ionization chamber; extrapolation chambers; proportional chambers. Geiger-Mueller counters; scintillation detectors; solid and liquid scintillators; semiconductor detectors; photographic emulsions; thermoluminescent detectors; nuclear track detectors; neutron detectors; detectors using (n,γ) or (n,p) reactions, activation; imaging detectors.
11. The level of natural background radiation. The radon problem. Man-made radiation background.

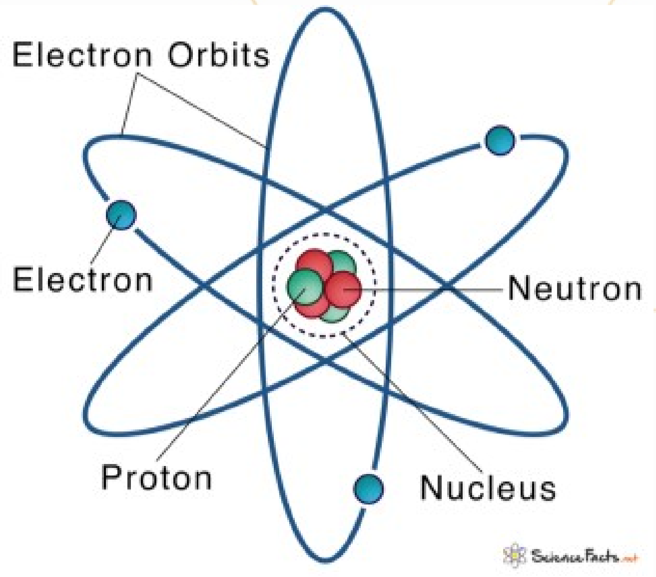
The basic unit of matter is the atom.

The basic atomic model, as described by Ernest Rutherford and Neils Bohr in 1911, consists of a positively charged core surrounded by negatively-charge shells.

The central core, called the *nucleus*, contains protons and neutrons.

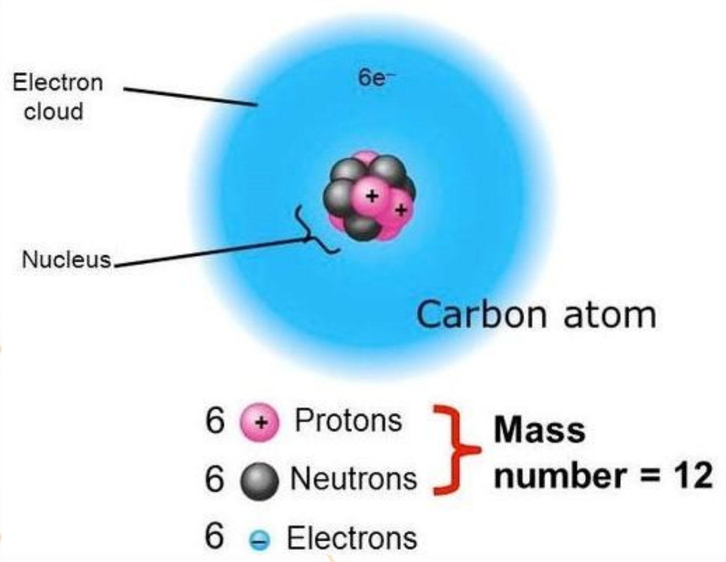
Nuclear forces hold the nucleus together.

The shells are formed by electrons, which exist in structured orbits around the nucleus.



Protons (p^+) are positively charged and located in the nucleus of the atom. The number of protons determines the element.

Neutrons (n) are uncharged and located in the nucleus of the atom.



https://www.nuclear-power.com/nuclear-engineering/radiation-protection/

Electrons (e^-) are negatively charged and travel in specific orbits with specific energy levels around the nucleus.

Atom is electrically neutral if the total electron charge equals the total proton charge.

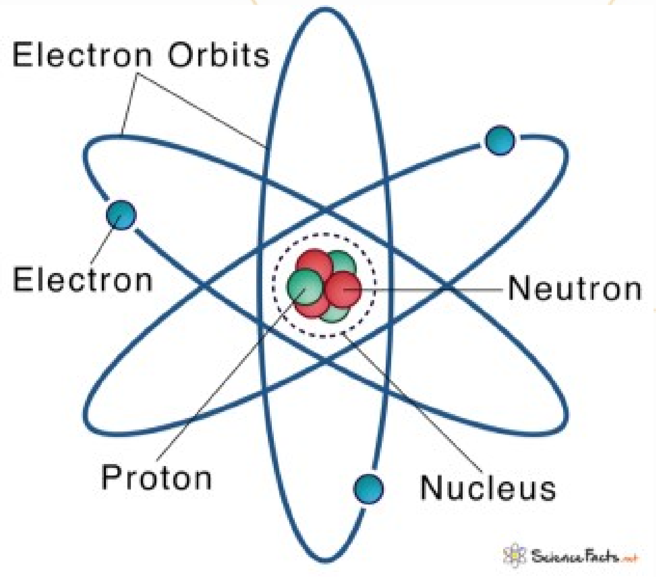
Electrons are bound to the positively charged nucleus by electrostatic attraction.

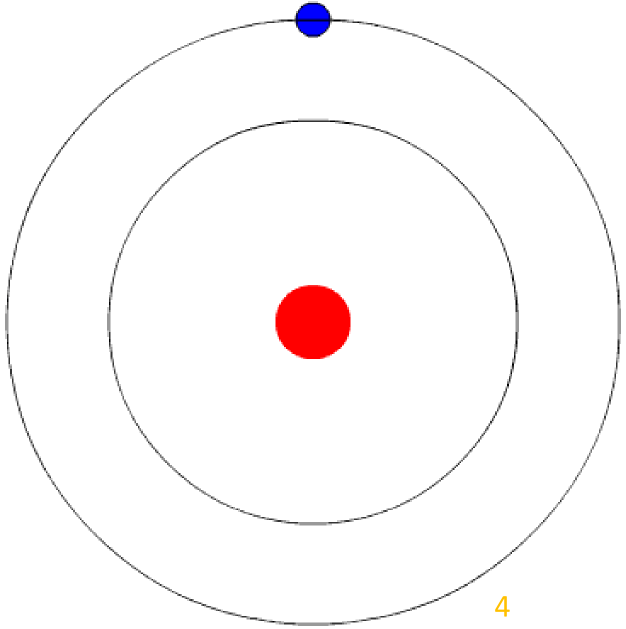
The number of electrons and protons determines the overall electrical charge of the atom.

The term *ion* is used to define atoms or groups of atoms that have a net positive or negative electrical charge.

The energy of particles (protons, neutrons, electrons) is usually given in electron volts (eV). The electron volt is defined as the energy of an electron that has been accelerated through an electron potential of one volt.

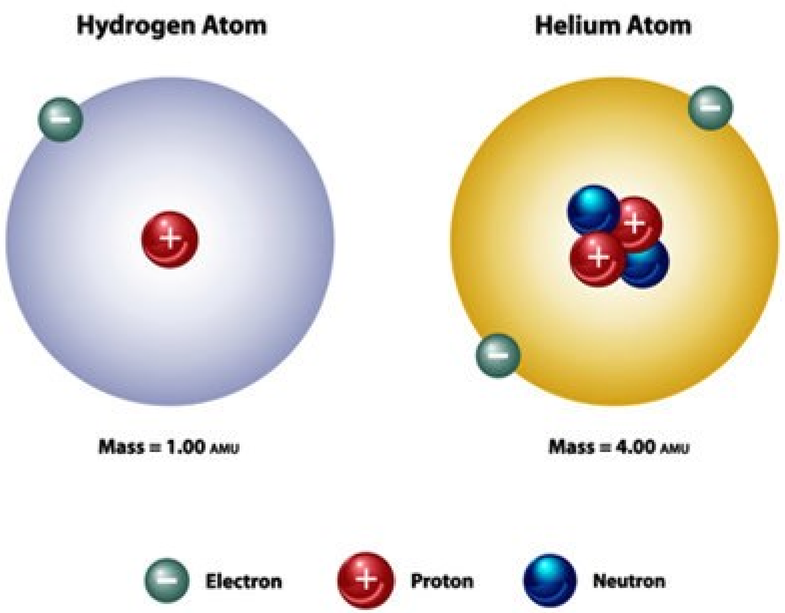
The eV is a very small amount of energy and therefore keV (thousand electron volts) and MeV (million electron volts) are used. The energy of visible light quant is about 2-3 eV.





A change in electron energy is possible due to the emission or absorption of energy by an atom in the form of electromagnetic waves.

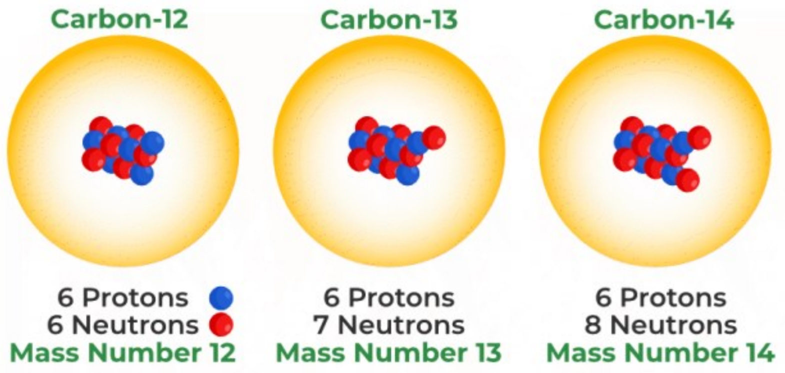
The number of protons in the nucleus of an element is called the atomic number (Z). Atomic numbers are all integers. For example, a hydrogen atom has one proton in the nucleus, so the atomic number of hydrogen is 1. A helium atom has two protons in the nucleus, which means the atomic number is 2. Uranium has ninety-two protons in the nucleus and, therefore, has an atomic number of 92.



Nuclide can be specified by using the chemical symbol, with the mass number written as a superscript at the upper left of the symbol: ^{A}X
where: X is a symbol for element, A is a mass number (number of protons (Z) plus the number of neutrons (N)). For example, the notation for uranium-238 would be ^{238}U.

Atoms that have the same number of protons, but different numbers of neutrons are called *isotopes*. *Isotopes* have the same chemical properties; however, the nuclear properties can be quite different.

The mass number can be used with the name of the element to identify which isotope of an element we are referring to. If we are referring to the isotope of carbon that has a mass number of 12, we can write it as Carbon-12. If we are referring to the isotope of mass number 13, we write it as Carbon-13.

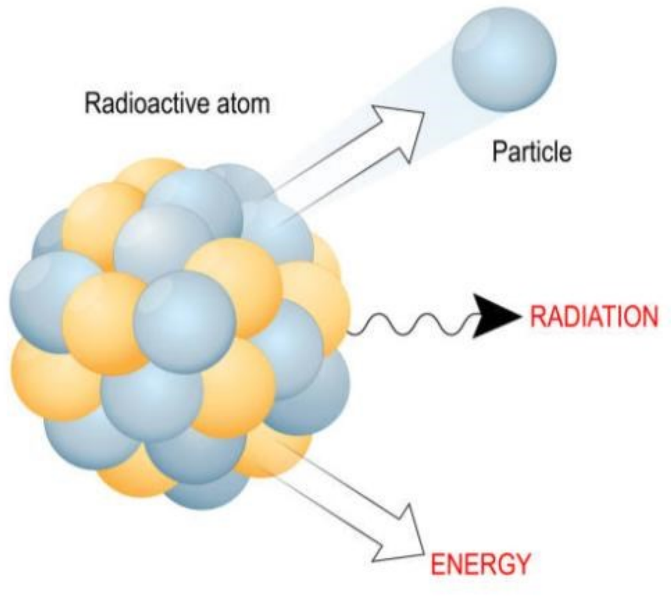


Isobars are atoms (nuclides) of different chemical elements that have the same number of nucleons. Correspondingly, isobars differ in atomic number (or number of protons) but have the same mass number. An example of a series of isobars is ^{40}S, ^{40}Cl, ^{40}Ar, ^{40}K, and ^{40}Ca. While the nuclei of these nuclides all contain 40 nucleons, they contain varying numbers of protons and neutrons.

Only certain combinations of neutrons and protons result in stable atoms. If there are too many or too few neutrons for a given number of protons, the resulting nucleus will have excess energy.

The unstable atom will become stable by releasing excess energy in the form of particles or energy (quanta).

This emission of particles or energy from the nucleus is called radiation. These unstable atoms are also known as radioactive material.



The property of certain nuclides to spontaneously emit radiation is called radioactivity.

The term radionuclide has been coined to refer to these radioactive nuclides.

There are on the order of 200 stable nuclides and over 1100 unstable (radioactive) nuclides.

The emission of a particle or energy (electromagnetic radiation) in order to reach a more stable configuration usually results in the formation of a *new element*.

Following this *transmutation* the nucleus is usually more stable.

As the energy of the nucleus is reduced, the nucleus is said to disintegrate.

Radioactive decay is the process of spontaneous transformation of the nucleus.

The *radioactive decay constant* (λ) is a characteristic of unstable radionuclides that spontaneously decay at different rates to a more stable atomic configuration; the larger the decay constant, the more rapidly the parent radionuclide is depleted with time.

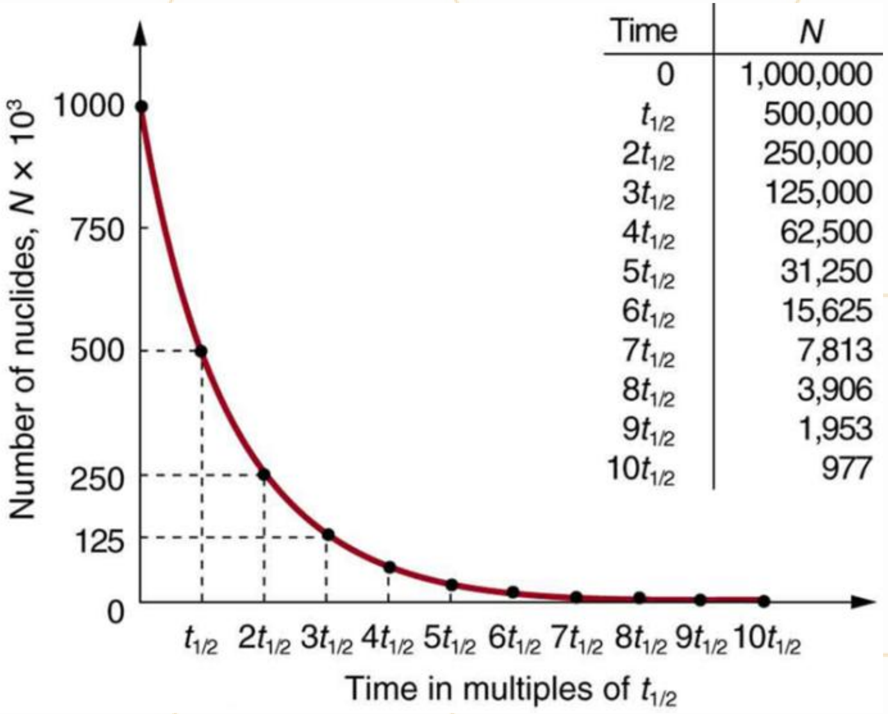
$$T_{1/2} = \frac{\ln 2}{\lambda} \approx \frac{0.693}{\lambda} \approx 0.693\tau$$

Radioactive half-life ($T_{1/2}$); Radioactive decay constant (λ); Mean lifetime (τ)

The time required for half of the original population of radioactive atoms to decay is called the *half-life*.

The half-lives of some radioactive isotopes

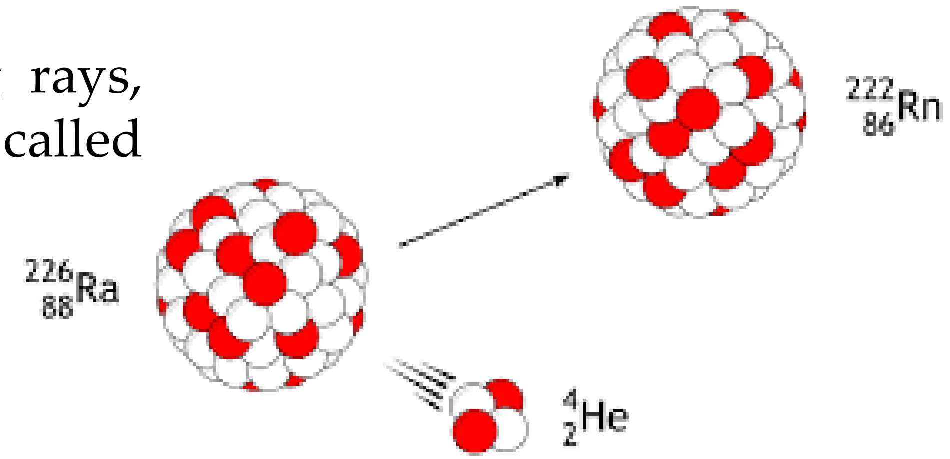
Radioactive isotope	Half-life
Uranium-238, $^{238}_{92}U$	4.5×10^{9} years
Carbon-14, $^{14}_{6}C$	5.7×10^{3} years
Radium-226, $^{226}_{88}Ra$	1.6×10^{3} years
Strontium-90 $^{90}_{38}Sr$	28 years
Iodine-131, $^{131}_{53}I$	8.1 days
Bismuth-214, $^{214}_{83}Bi$	19.7 minutes
Polonium-214, $^{214}_{84}Po$	1.5×10^{-4} seconds



Time	N
0	1,000,000
$t_{1/2}$	500,000
$2t_{1/2}$	250,000
$3t_{1/2}$	125,000
$4t_{1/2}$	62,500
$5t_{1/2}$	31,250
$6t_{1/2}$	15,625
$7t_{1/2}$	7,813
$8t_{1/2}$	3,906
$9t_{1/2}$	1,953
$10t_{1/2}$	977

Henri Becquerel first reported evidence of natural radioactivity in 1896. Becquerel demonstrated that uranium ore would darken a photographic plate shielded with opaque paper in much the same manner as X-rays.

He postulated that the uranium emitted very penetrating rays, similar to X-rays. The phenomenon was ultimately called radioactivity.

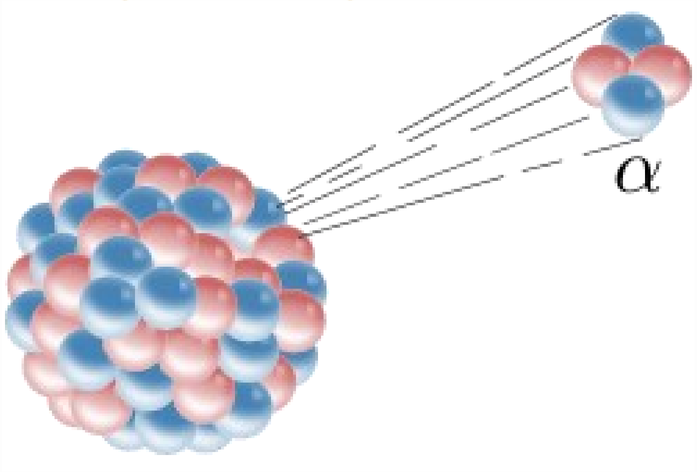


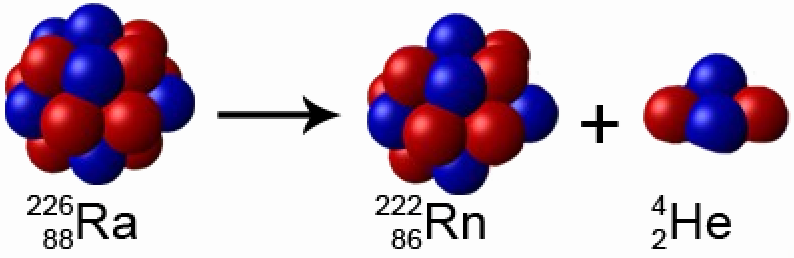
When a radioactive nuclide decays, a transmutation occurs.

The decay product, or daughter has become an atom of a new element with chemical properties different than original parent atom.

With each transmutation an emission from the nucleus occurs.

There are several modes of decay associated with each emission.





Alpha particles (α) are essentially a doubly charged helium nucleus (He^{2+}), consisting of two protons and two neutrons, which is emitted from the nucleus of an atom.

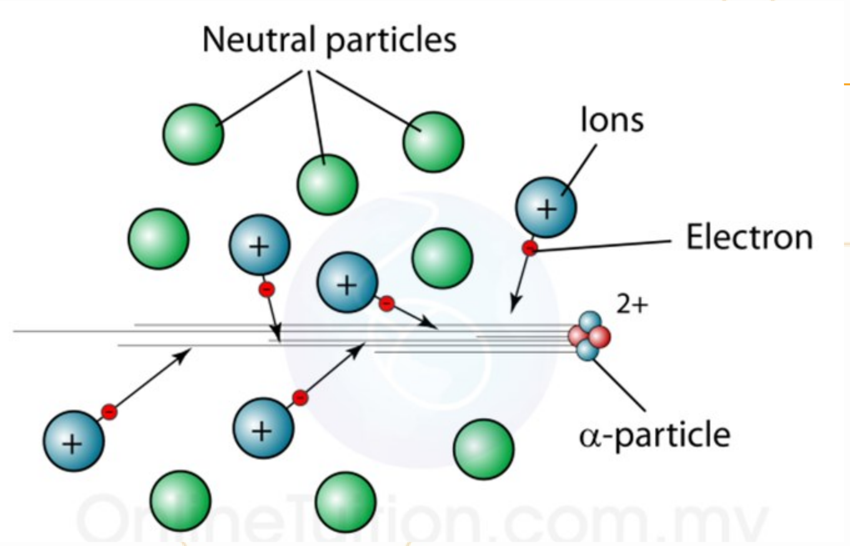
Only relatively heavy radioactive nuclides, like radium, uranium, thorium, and plutonium, decay by alpha emission. For example, Radium-226 decays by alpha emission to produce Radon-222.

The transformation of $^{A}_{Z}X$ nucleus to $^{A-4}_{Z-2}X$ nucleus is expressed as follows,

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + {}^{4}_{2}He$$

Here $^{A}_{Z}X$ is the parent nucleus and $^{A-4}_{Z-2}X$ is the daughter nucleus.

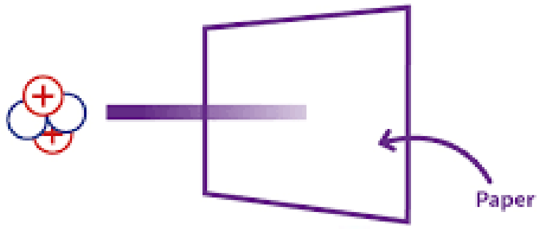
Alpha decay is monoenergetic, meaning that all alpha particles emitted by a particular isotope undergoing a particular nuclear transition have the same energy.



The alpha particle's positive charge (He^{2+}) strips electrons (e^-) from nearby atoms as it passes through the material, thus ionizing these atoms.

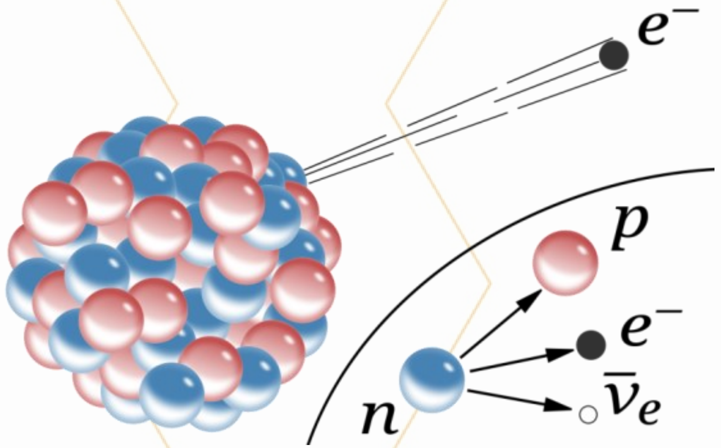
Alpha particles interact very strongly with any material and deposit large amounts of energy in a short distance.

One alpha particle will cause tens of thousands of ionizations per centimeter in air. This large energy deposit limits the penetrating ability of the alpha particle to a very short distance. This range in air is about one to two inches.

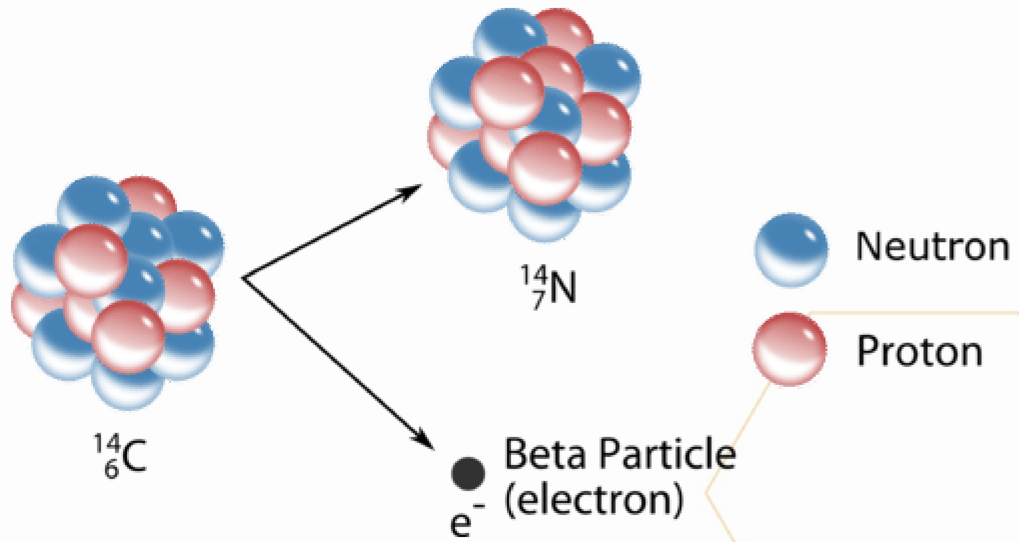


From a radiation safety standpoint, a thin absorber such as a sheet of paper or the dead layer of skin easily stops alpha particles. External exposure of the body to such alpha sources does not present a great hazard. Inside the body, however, alpha emitters are highly significant. Because the alpha particle undergoes many interactions with surrounding atoms, it deposits all its energy in a very small volume ($3x10^{-9}$ cm^3 in muscle).

An energy deposit of this magnitude within a cell nucleus will virtually guarantee cell destruction. For this reason, extreme precautions must be taken to prevent sources of alpha radiation from entering the body by inhalation, ingestion, or puncture.



Beta particles (β) are high-speed electrons emitted from the nucleus of an atom.
In beta decay, a neutron is converted to a proton and an electron, and the electron (or beta particle) is promptly ejected from the nucleus forming a new element with an atomic number increased by 1.



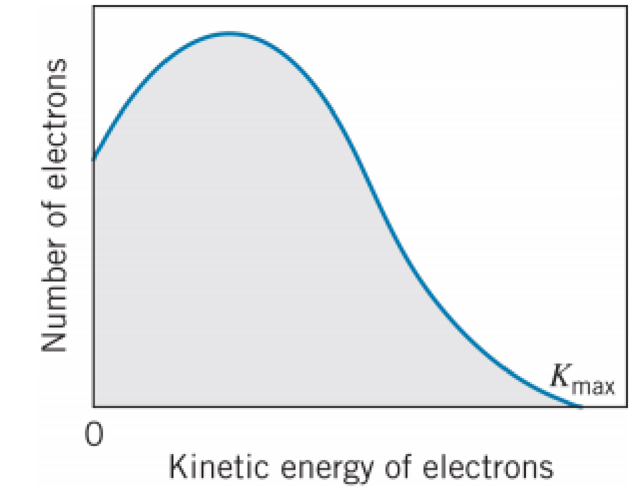
For example, carbon-14 (^{14}C), which has eight neutrons and six protons, decays by beta decay. After the emission of the beta particle, the nucleus contains seven protons and seven neutrons. Its mass number remains the same, but its atomic number increases by one. The new element with atomic number 7 is nitrogen.

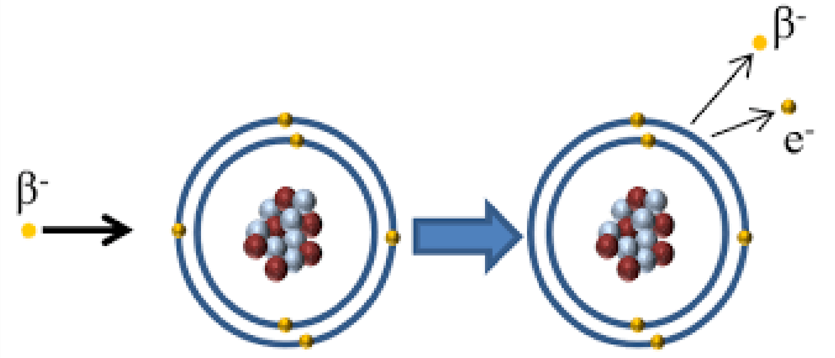
The most commonly used beta-emitting radionuclides are ^{3}H, ^{14}C, ^{32}P, ^{33}P, and ^{35}S.

Beta particles are emitted with a continuous spectrum of kinetic energies ranging from zero to the maximum value of the decay energy, K_{max}. However, most beta particles are ejected with energies lower than this maximum energy.

The mean energy of beta particles is about $1/3K_{max}$.

The shape of the beta energy spectrum for various radioisotopes and values for K_{max} is characteristic for a particular isotope.



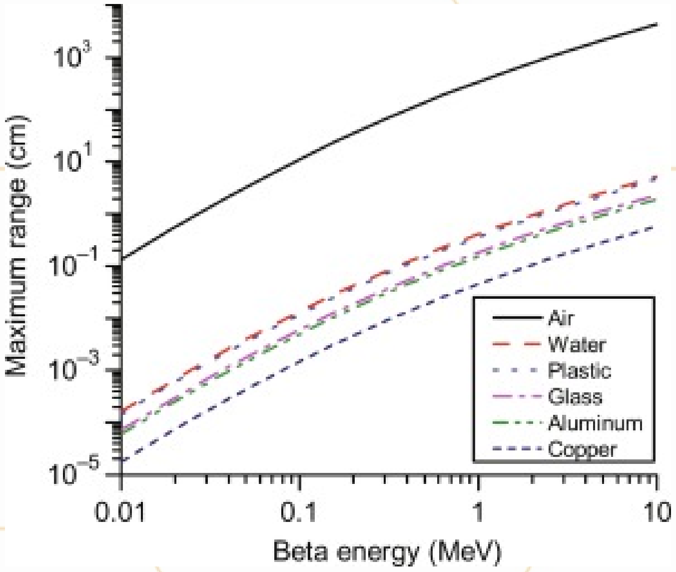


Beta radiation causes ionization by displacing electrons from their orbits. Ionization occurs due to the repulsive force between the beta particle (β^-) and the electron (e^-), which both have a charge of minus one.

Beta particles have a finite range, in the air and in other materials, which is linearly related to their energy.

The range of beta particles in the air is about 3-4 m per MeV.

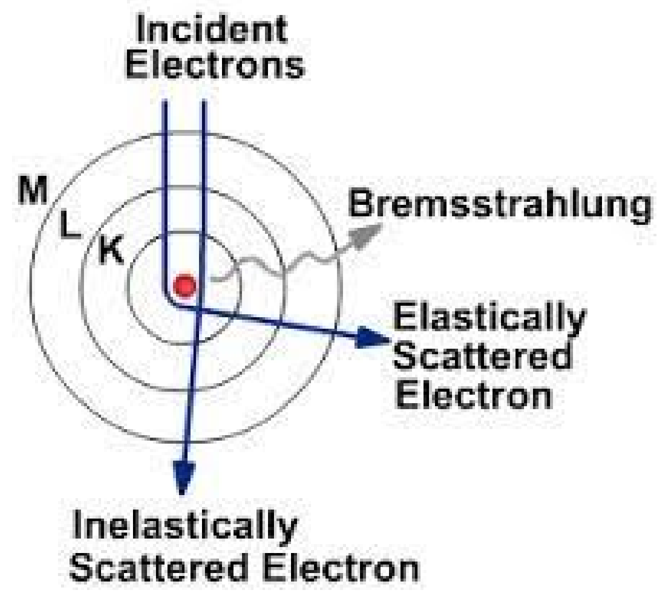
Plastic, glass, aluminum foil, or safety glasses can shield most beta particles.

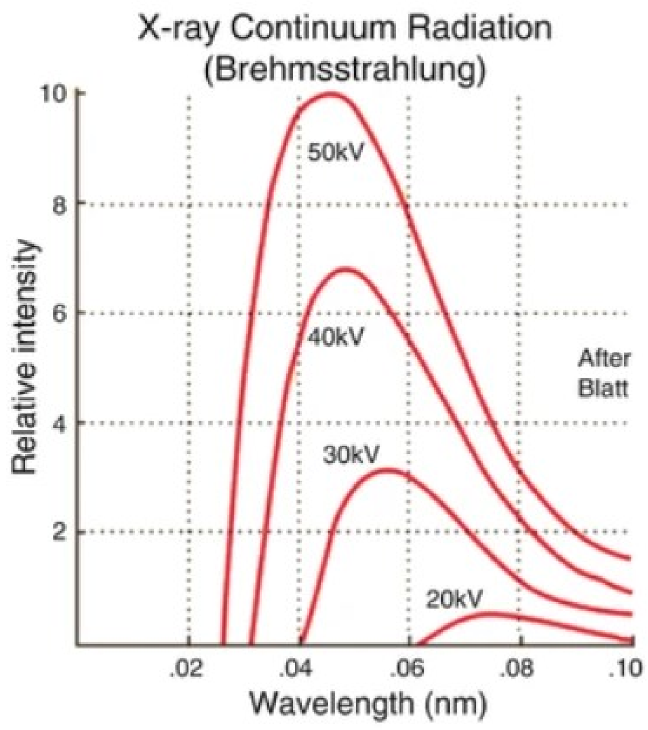


Charged particles, including beta particles, lose energy in an absorbing material by excitation, ionization, and radiation. Radiation energy losses of charged particles are important and are termed bremsstrahlung, which in German means “braking radiation”.

This process occurs when the charged particle decelerates in an absorber with an attendant creation of an X-ray (or bremsstrahlung) radiation.

This radiation is more penetrating than the original beta particle.

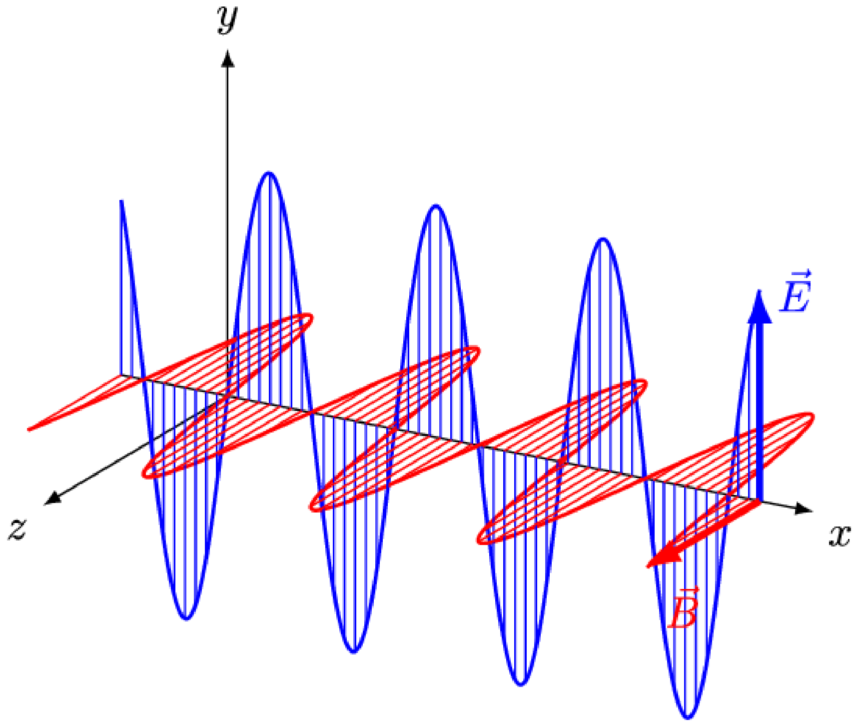




The fraction of beta energy that contributes to the production of bremsstrahlung is directly proportional to both the atomic number of the absorber and the energy of the beta radiation.

To prevent the creation of bremsstrahlung radiation, high-energy beta emitters must be shielded with the material having a low atomic number.

https://link.springer.com/chapter/10.1007/978-3-319-51177-1_2/figures/19



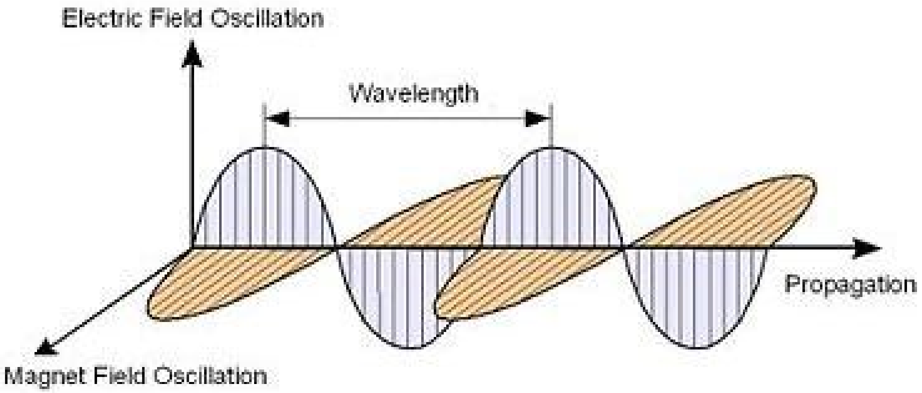
Gamma rays (γ) and X-rays are electromagnetic radiation and have no electrical charge.

X-rays originate in the atoms at electron transition from higher to lower energy levels.

Gamma rays result from the rearrangement of protons and neutrons that make up the nucleus and like electrons in the shells of an atom can only change their energy discretely.

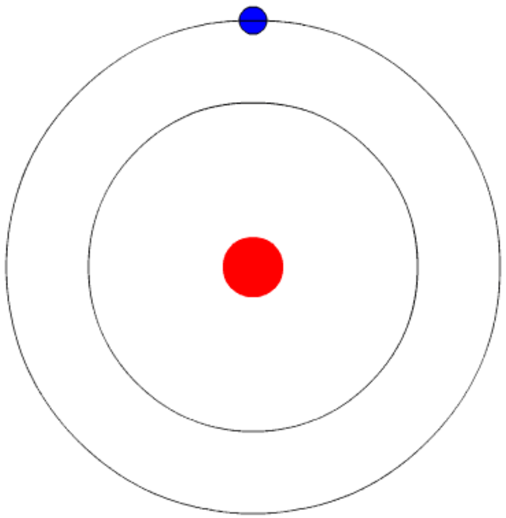
Gamma and X-rays are both emitted in discrete packets of energy known as *photons* and travel at the speed of light.

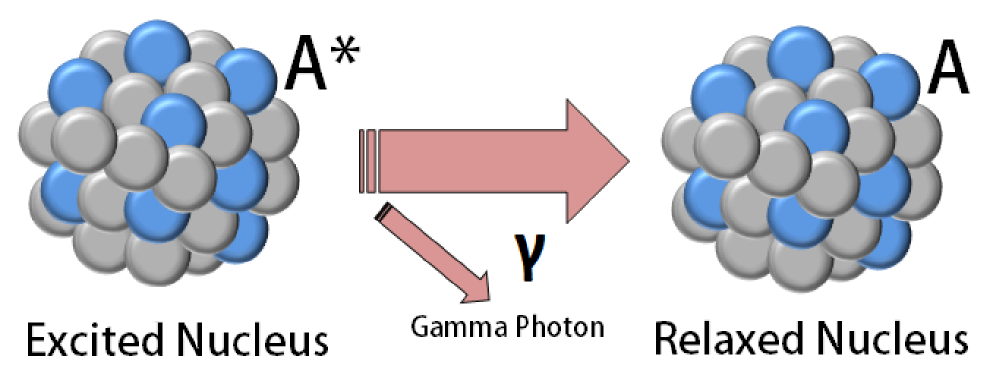
Gamma rays from radioactive decay are in the energy range from a few keV to ~8 MeV, corresponding to the typical energy levels in nuclei with reasonably long lifetimes.



Gamma rays typically have more energy than other forms of electromagnetic radiation.

The properties of these photons is determined by their wavelength or frequency.

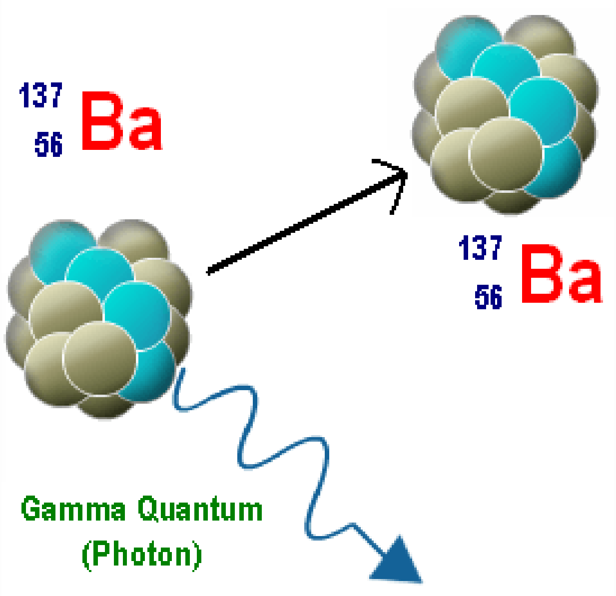




Gamma radiation may accompany any of the other decay modes.

Nuclear decay reactions resulting in a transmutation generally leave the resultant nucleus in an excited state.

Nuclei, in this excited state, may reach an unexcited or ground state by the emission of a gamma ray.

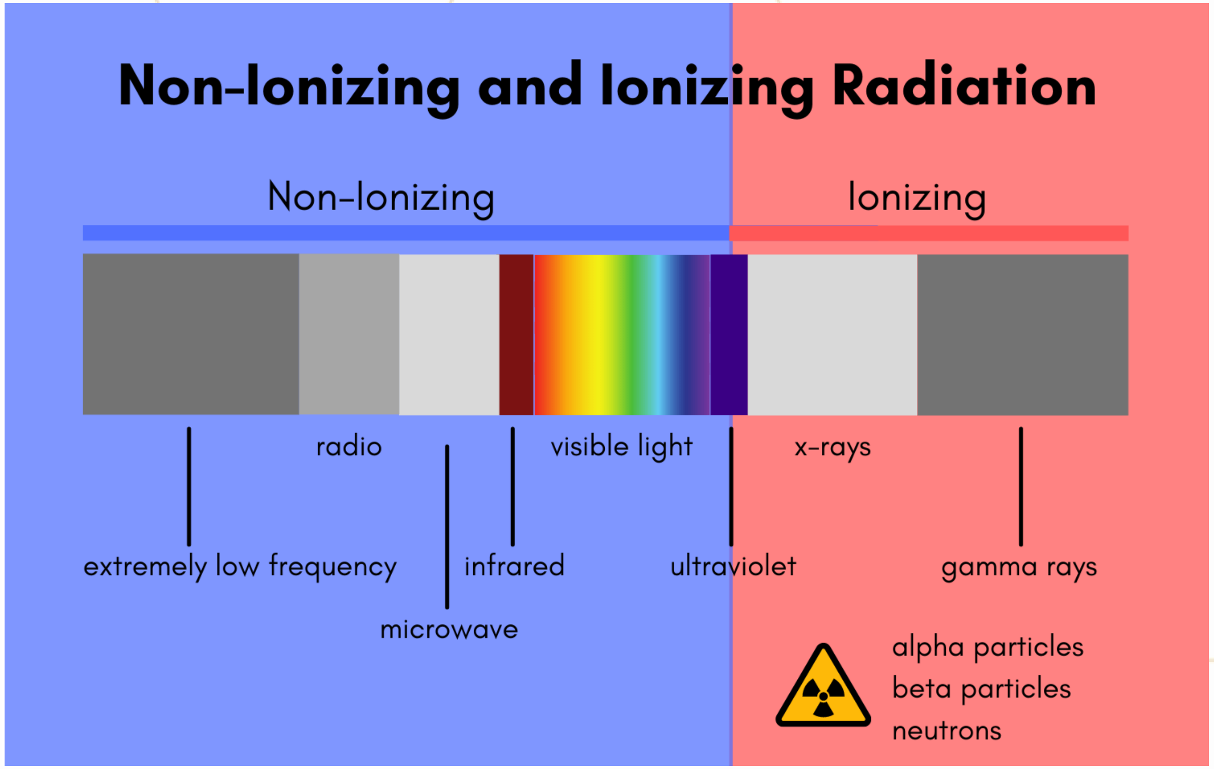


If a nucleus emits a gamma-ray, atomic and mass numbers of the daughter nucleus remain the same, but the daughter nucleus will form a different energy state of the same element.

Nuclides with equal proton number and mass number (thus making them by definition the same isotope) but in a different energy state are known as nuclear isomers.

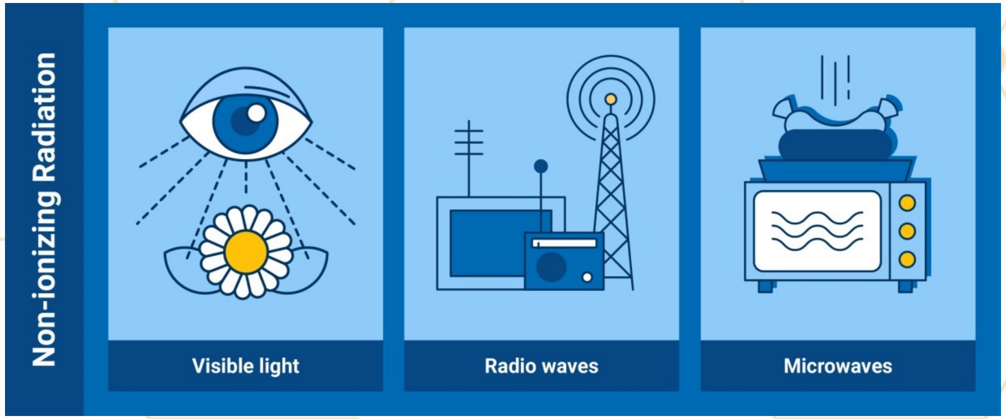
Isomers are usually indicated with a superscript *m*: ^{241m}Am or ^{110m}Ag.

Gamma decay typically accompanies other forms of decay, such as alpha or beta decay. After a beta decay nuclei usually contain too much energy to be in their final stable or daughter state.



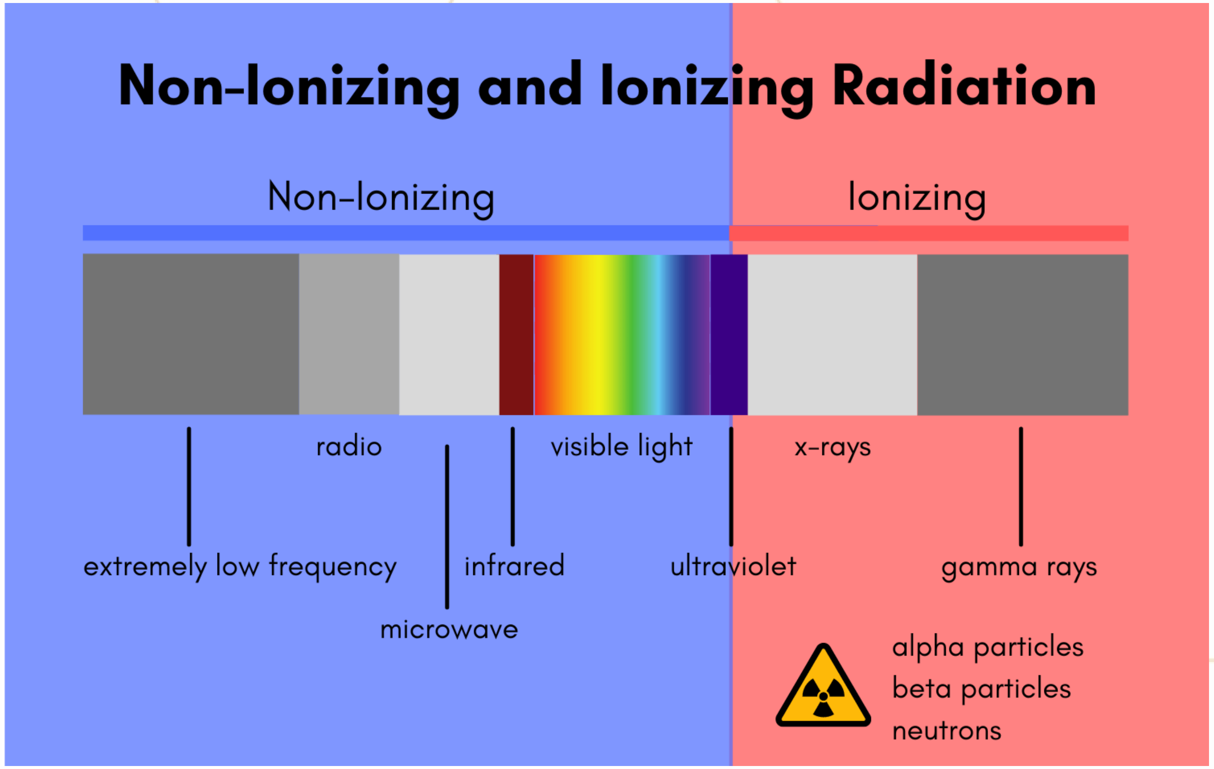
People use and are exposed to non-ionizing radiation sources every day. This form of radiation does not carry enough energy to ionize atoms or molecules.

Microwave ovens, global positioning systems, cellular telephones, television stations, FM and AM radio, baby monitors, cordless phones, garage-door openers and ham radios all use non-ionizing radiation.

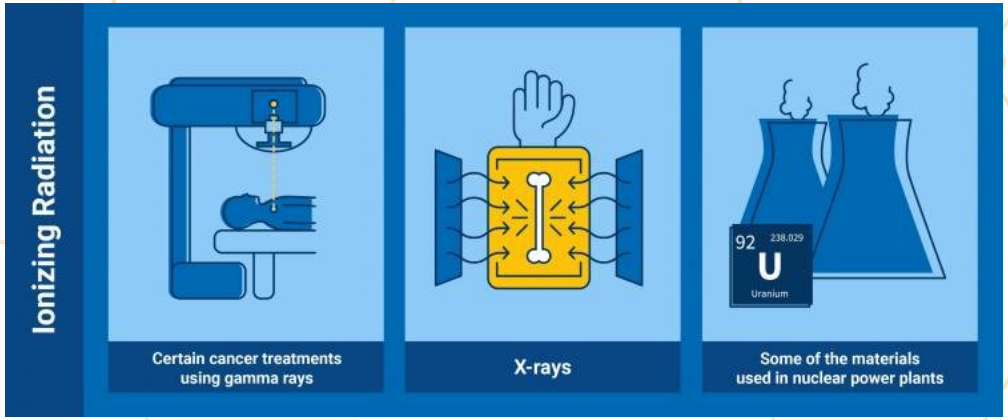


Other forms include the Earth's magnetic field and magnetic field exposure from proximity to transmission lines, household wiring and electrical appliances.

These are defined as extremely low frequency (ELF) waves.



Ionizing radiation is a type of radiation of such energy that it can detach electrons from atoms or molecules, which causes changes at the atomic level when interacting with matter including living organisms. Such changes usually involve the production of ions (electrically charged atoms or molecules) – hence the term "ionizing" radiation.

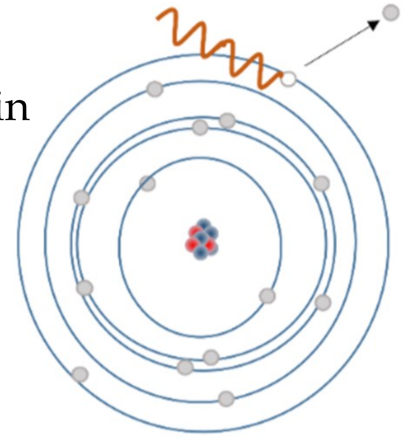


In high doses, ionizing radiation can damage cells or organs in our bodies or even cause death. In the correct uses and doses and with the necessary protective measures, this kind of radiation has many beneficial uses, such as in energy production, in industry, in research and in medical diagnostics and treatment of various diseases, such as cancer.

A radiation can be considered as ionizing if deposited energy is high enough to ionize the traversed material

Gamma Rays / X-rays (photons)

For energies lower than 50 MeV there are three main processes by which photons interact with matter:

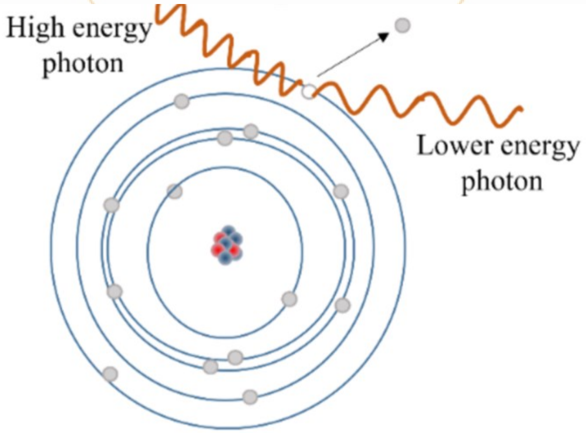


1. Photoelectric effect

The photon is completely absorbed. Its energy $E\gamma$ liberates an electron bound with energy E_B, and provides it with kinetic energy E_K.

$$E_K = E\gamma - E_B$$

This effect dominates with low-energy photons interacting with heavier elements

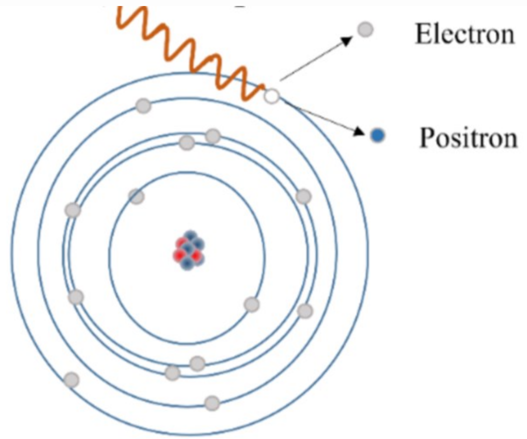


2. Compton scattering

An incident photon with energy $E_{\gamma 1}$ liberates an orbiting electron, yielding a recoil electron with kinetic energy E_K and a lower energy scattered photon with energy $E_{\gamma 2}$

$$E_{\gamma 1} = E_K + E_{\gamma 2}$$

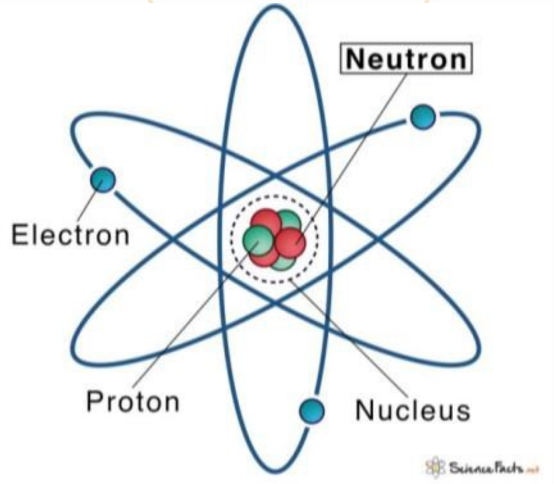
In water or biological tissues, this effect dominates at energies above 50 keV



3. Pair production

An incident photon with energy $E_{\gamma 1}$ is converted into an electron and a positron.

This interaction starts occurring at energies higher than 1 MeV. Unlike electron, positron will eventually disappear annihilating one electron of surrounding material. Positron-electron pair is converted into two photons with energy of about 0.5 MeV

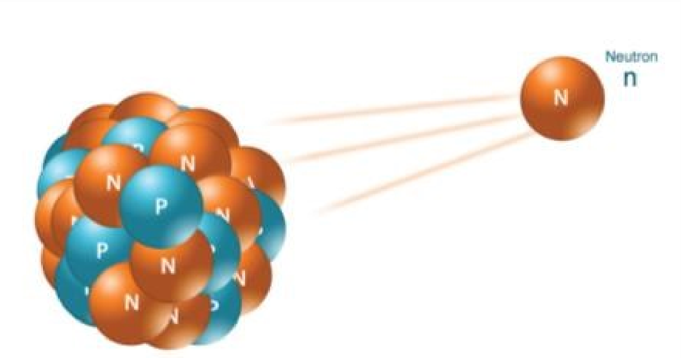


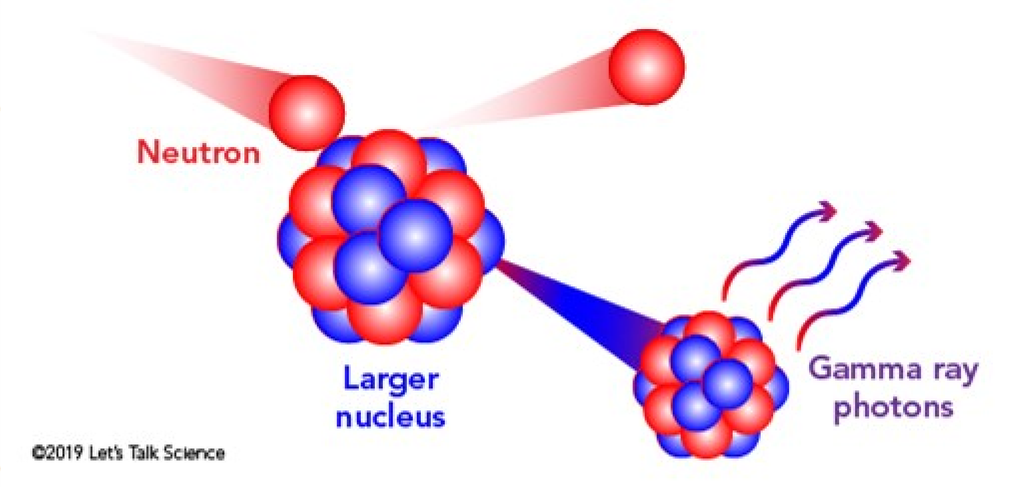
The neutron has no electric charge, and its mass is marginally greater than that of a proton and nearly 1839 times greater than that of an electron.

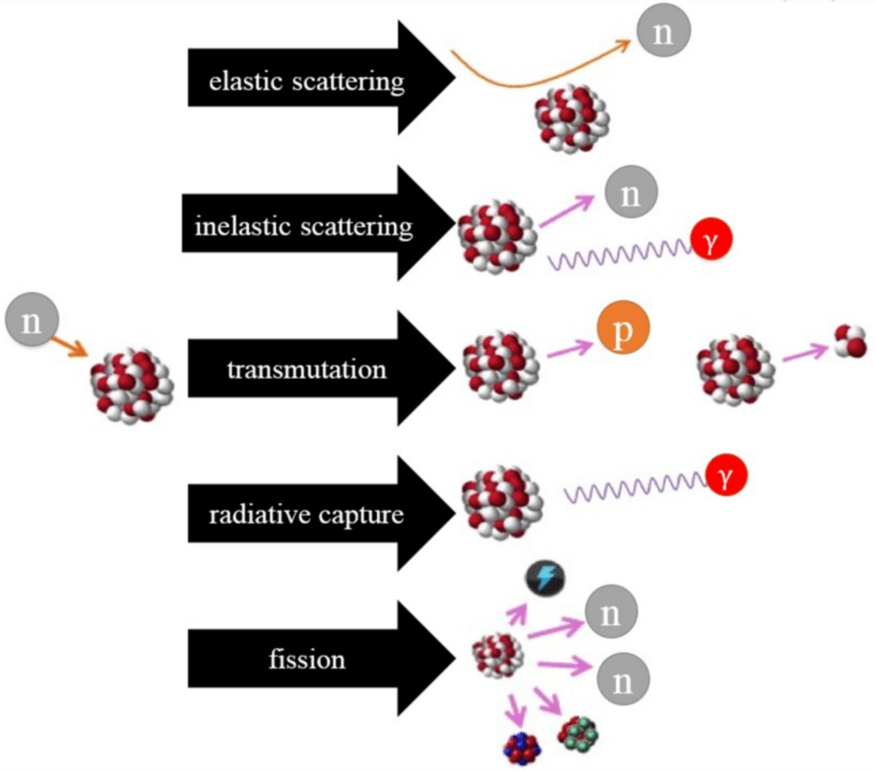
Neutrons make up more than half of all visible matter.

Neutrons are neutral particles, so the electric fields of the electron cloud and the nucleus do not affect the neutron's flight - they travel in a straight line in matter, deviating from their path only due to a collision with a nucleus to be scattered in a new direction or absorbed (neutrons collide with nuclei, not with atoms).

However, neutron interactions are largely ionizing - when neutron absorption results in gamma emission and a gamma ray (photon) subsequently removes an electron from an atom, or a nucleus recoiling from a neutron interaction is ionized and causes more traditional further ionization in other atoms.







The types of reactions that are possible and their probability depends on the neutron kinetic energy. Neutrons are classified according to energy.

The following is approximate: Thermal (0.025 eV) -- Slow (< 10 eV) -- Intermediate (10 eV – 100 keV) – Fast (>100 keV)

Typical Fate of Neutrons:

Neutrons are born fast. They slow down due to scattering (referred to as moderation) until they reach thermal energies. Finally, they are absorbed by a target nucleus.

Fast neutron → Thermal Neutron → Capture

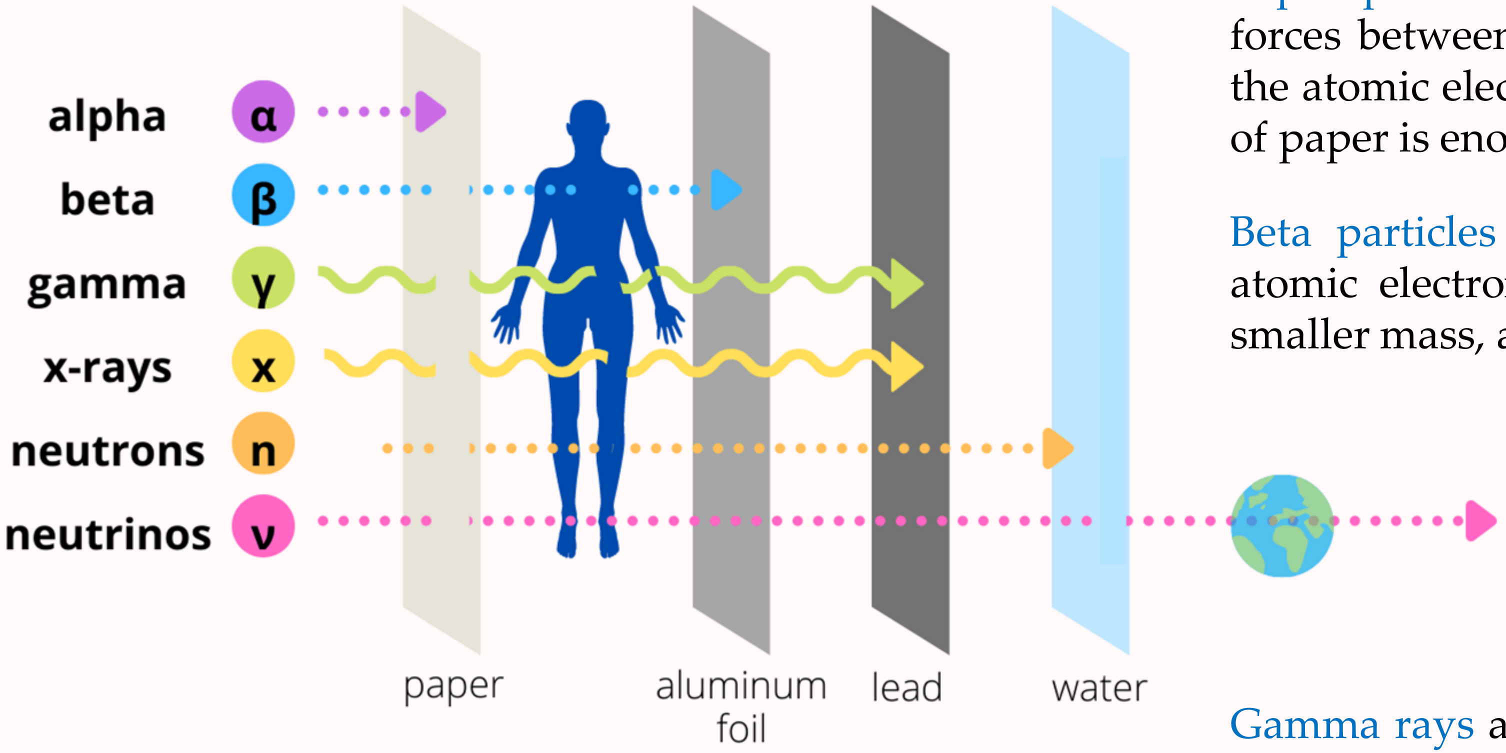
Elastic scattering is a billiard ball type of collision where kinetic energy is conserved, i.e., the total kinetic energy is the same before and after the collision

Types of neutron-nuclear reactions:

- Elastic Scattering Reaction
- Inelastic Scattering Reaction
- Neutron Absorption
- Radiative Capture
- Nuclear Fission
- Neutron Emission
- Charged particles formation

Elastic scattering is the most likely interaction for almost all nuclides and neutron energies. The greatest amount of energy can be transferred from the neutron to a target nucleus when the latter has the same mass as the neutron. As such, the lower the atomic mass number of the target, the more effective it is as a moderator. Moderators (e.g., water, paraffin, plastic, and graphite) slow neutrons by elastic scattering.

The remaining energy is given to the target nucleus as excitation energy and produce emission of secondary charged particles (like protons, alpha particles or nuclear fragments heavier than carbon, oxygen, nitrogen or hydrogen) which are responsible for tissue ionization and for biological effect.



Alpha particles interact with matter primarily through Coulomb forces between their positive charge and the negative charge of the atomic electrons within the absorber. The thickness of a sheet of paper is enough to stop all the alphas.

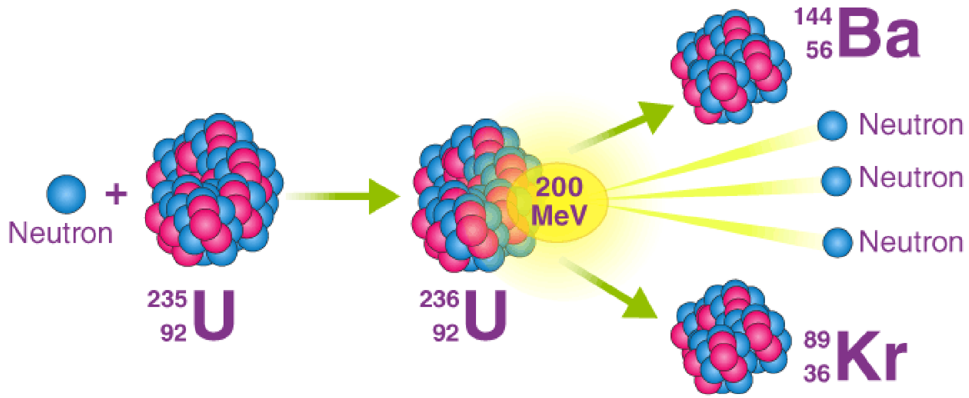
Beta particles also interact through Coulomb forces with the atomic electrons. Betas have much higher speeds due to their smaller mass, and smaller impulses are involved in collisions.

Beta penetration into matter is thus considerably greater than alphas, but because of the nature of the Coulomb force interactions, betas too are stopped by little matter (compared to gammas).

Gamma rays are the most penetrating type of common radiation from radioactive decay. Lead shielding blocks gamma radiation.

Neutrons can penetrate the human body and lead shielding, but a thick layer of water or concrete absorbs them.

Overall, neutrinos are the most penetrating form of radiation. Neutrinos are energetic, nearly-massless particles that are nearly unstoppable. Neutrinos pass through the Earth, stars, and entire galaxies, very rarely interacting with any matter.



When Uranium-235 atom is bombarded with a neutron, it splits into two lighter nuclei Barium and Krypton.

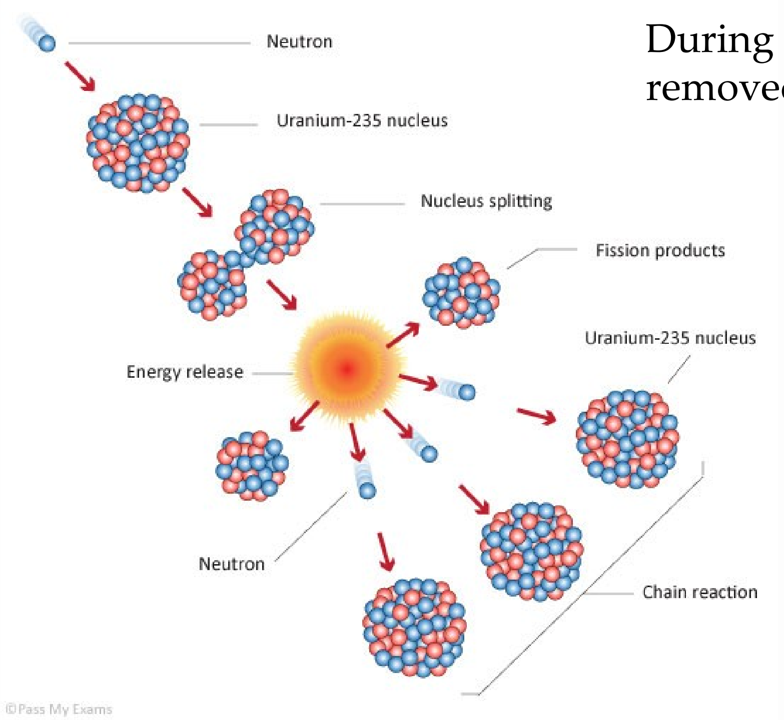
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n + 210MeV$$

Nuclear fission is a splitting of uranium and plutonium isotopes into atoms of lighter elements as a result of bombarding by neutrons.

In addition to this formation of lighter atoms, free neutrons are emitted in the fission process, along with considerable energy.

Nuclear fission is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments.

The complete fission of 1 kg of uranium or plutonium produces of about 17.5 kilotons of TNT-equivalent explosive energy.



During the Nuclear fission some of the mass of the nucleus gets converted into energy. This mass is removed from the total mass of the original particles, and the mass is missing in the resulting nucleus:

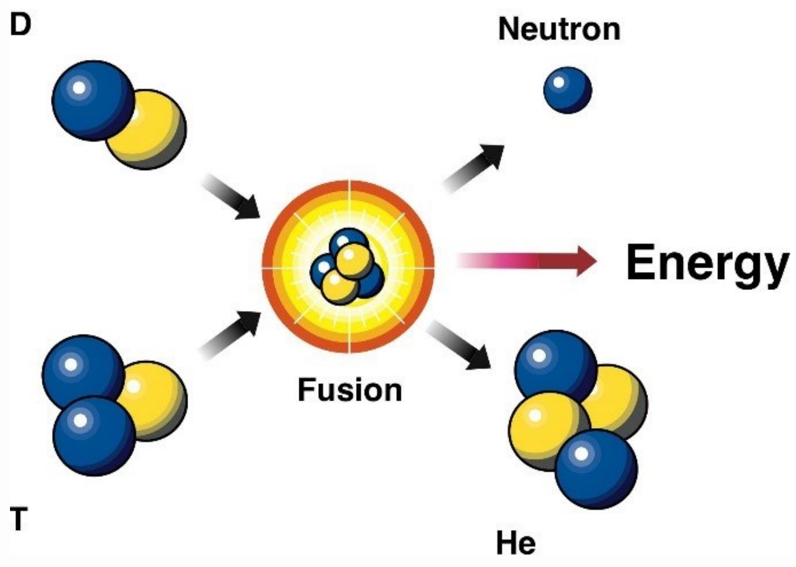
$$E = \Delta mc^2$$

Chain reaction: the neutrons released in the fission can go on to produce fission in other Uranium-235 nuclei. These Uranium nuclei split to produce further neutrons which in turn trigger fission in further Uranium-235 nuclei and so on.

Chain reactions are made use of in nuclear reactors and atomic bombs.

In an atomic bomb, uranium is used above a critical size to get an uncontrolled chain reaction by ensuring all the available fissile material undergoes fission in the minimum time possible.

In nuclear reactors, the concentration of Uranium-235 is much less, and the chain reaction is controlled in order to reduce it and more importantly stop it if required.



Nuclear fusion is the process in which the nuclei of light elements combine, or fuse together, to give heavier nuclei.

An example of a fusion reaction is that of deuterium ($^{2}_{1}H$, D) and Tritium ($^{3}_{1}H$,T) nuclei fusing together to give a helium nucleus.

Deuterium and tritium are isotopes of hydrogen. The reaction is as follows:

$$^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + 18.3MeV$$

This reaction releases massive amounts of energy

Fusion requires extremely high temperatures and pressures to overcome the electrostatic repulsion between positively charged atomic nuclei.

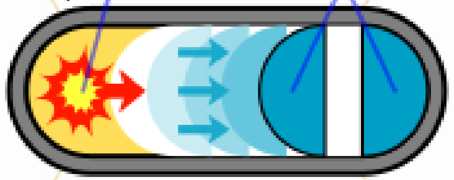
The potential benefits of nuclear fusion:

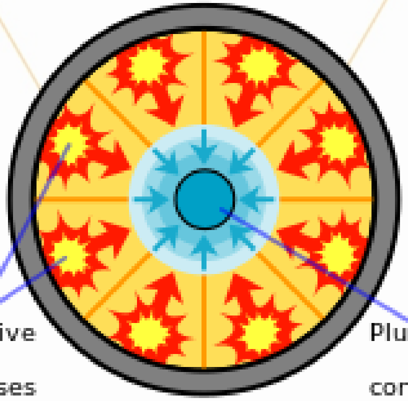
Abundant fuel supply: deuterium can be extracted from seawater, while tritium can be produced from lithium, making fusion fuel abundant and accessible worldwide.

Low environmental impact: fusion reactions produce no greenhouse gases or long-lived radioactive waste, making it a clean and sustainable energy source.

High energy density: fusion has a much higher energy density compared to fossil fuels or nuclear fission, meaning that a small amount of fusion fuel can generate a large amount of energy.

Safety: fusion reactions are inherently safe, as any disturbance in the plasma conditions would cause the reaction to stop, eliminating the risk of a runaway reaction or meltdown.

(1) 

(2) 

In fission weapons, a mass of fissile material (enriched uranium or plutonium) is forced into *supercriticality*—allowing an exponential growth of nuclear chain reactions — either by shooting one piece of sub-critical material into another (1) or by compression of a sub-critical sphere or cylinder of fissile material using chemically fueled explosive lenses (2).

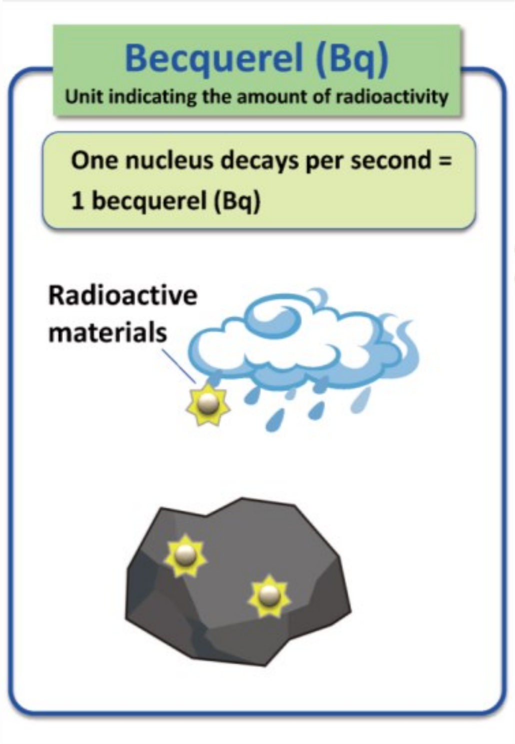
The amount of energy released by fission bombs can range from the equivalent of just under a ton to upwards of 500,000 tons (500 kilotons) of TNT (4.2 to 2.1×10^6 GJ)

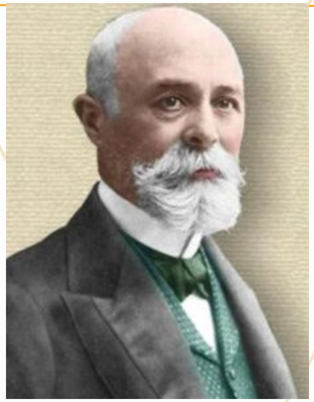
All fission reactions generate fission products, the remains of the split atomic nuclei. Many fission products are either highly radioactive (but short-lived) or moderately radioactive (but long-lived), and as such, they are a form of *radioactive contamination*. Fission products are the principal radioactive component of *nuclear fallout*.

Another source of radioactivity is the burst of free neutrons produced by the weapon.

Nuclear fallout is the residual radioactive material propelled into the upper atmosphere following a nuclear blast, so called because it "falls out" of the sky after the explosion and the shock wave has passed.

The amount and spread of *fallout* is a product of the size of the weapon and the altitude at which it is detonated. *Fallout* may get entrained with the products of a pyrocumulus cloud and fall as black rain. The radioactive dust consisting of fission products mixed with bystanding atoms that are neutron-activated by exposure is a form of *radioactive contamination*.





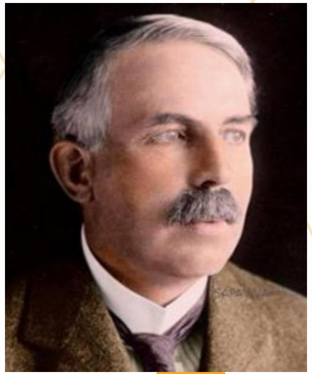
A measure of radioactivity (activity) is based on counting disintegrations per second. The SI unit of activity is the ***becquerel*** (***Bq***), equal to one reciprocal second.

The activity depends only on the number of decays per second, not on the type of decay, the energy of the decay products, or the biological effects of the radiation.

It can be used to characterize the rate of emission of ionizing radiation.

Specific activity is defined as the activity per quantity of atoms of a particular radionuclide. Specific activity is usually given in units of *Bq/g*.

Non-Si unit of radioactivity



Curie (symbol ***Ci***) is a non-SI unit of radioactivity: 1Ci = 3.7 x 10^{10} disintegrations per second.

Rutherford (symbol ***Rd***) is also a non-SI unit defined as the activity of a quantity of radioactive material in which one million nuclei decay per second: 1Rd = 1 x 10^{6} disintegrations per second.

Radiation exposure is defined as the sum of electrical charges (Δq) of all the ions of one sign produced in the air when all the electrons, liberated by photons in a volume of air whose mass is Δm, are completely stopped in the air. Radiation exposure is given the symbol X.

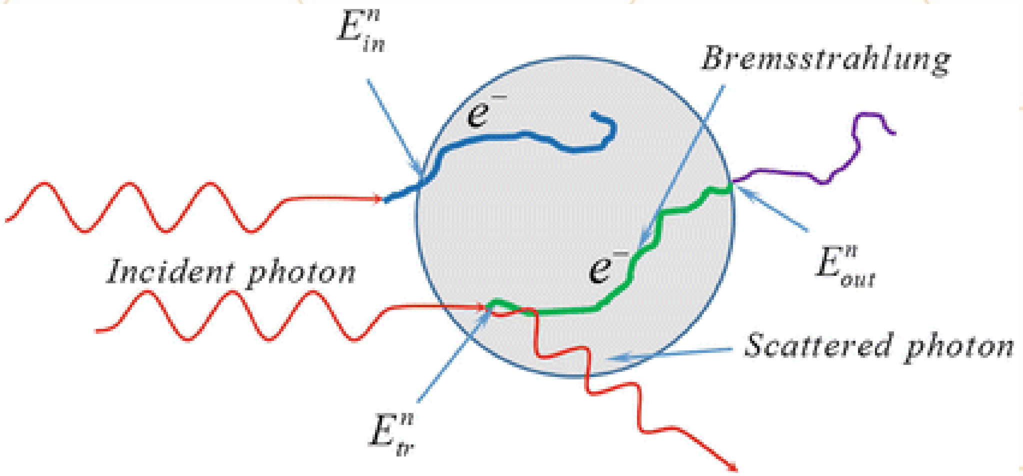
The SI unit of radiation exposure is the ***coulomb per kilogram*** (***C/kg***), in practice, the ***roentgen*** is used.

The ***roentgen*** (abbreviated ***R***) is the unit of radiation exposure.

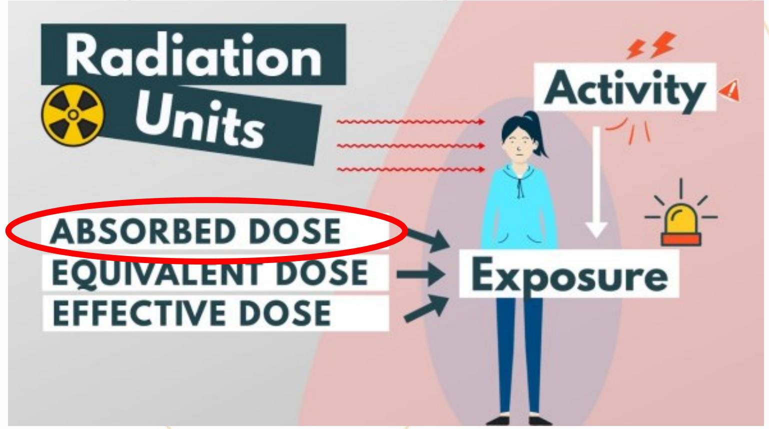
1 R means the amount of γ-radiation or X-rays required to liberate positive and negative charges of one electrostatic unit of charge (***esu***) in 1 cm^3 of dry air at standard temperature and pressure.

One roentgen (1 R) corresponds to 2.58 x 10^{-4} coulomb per kg of ions generated in air, and an exposure of one coulomb per kilogram is equivalent to 3876 roentgens.

Kerma is a measure of kinetic energy transferred from radiation to matter, and it is an acronym for "kinetic energy released per unit mass." Kerma is given the symbol ***K***, measured by the SI unit, the ***gray***.

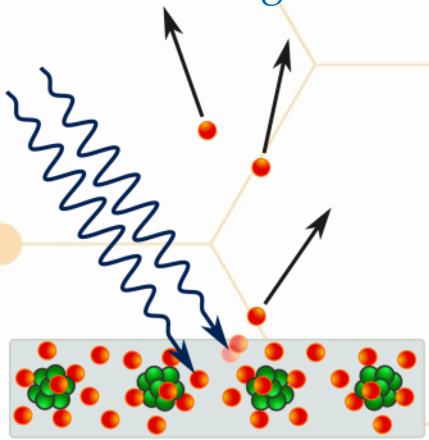


https://www.nuclear-power.com/nuclear-engineering/radiation-protection/quantities-and-units-of-radiation/

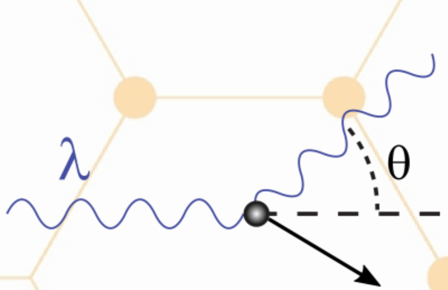


The dose is defined as the amount of energy deposited by ionizing radiation in a substance. The absorbed dose will depend on the type of matter which absorbs the radiation. The absorbed dose is given the symbol D.

There are three key interaction mechanisms of gamma rays with matter.



Photoelectric effect



Compton scattering

Units of absorbed dose:

1 ***Gray*** (***Gy***) is equivalent to a unit of energy (joule) deposited in a kilogram of a substance (SI system unit). One gray is a large amount of absorbed dose. A person who has absorbed a whole-body dose of 1 Gy has absorbed one joule of energy in each kg of body tissue.

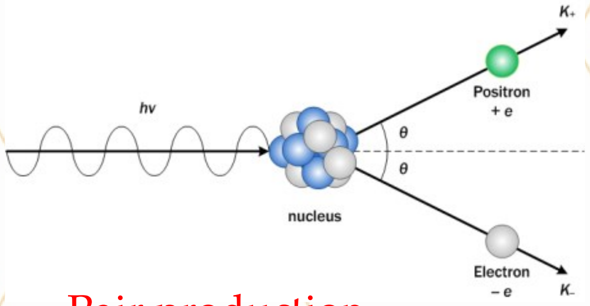
1 ***Rad*** (***R***) is equivalent to depositing one hundred ergs of energy in one gram of any material (is a unit of energy and 1 erg corresponds to 10^{-7} joules). 1 Rad is a significantly lower dose than one gray.

A person who has absorbed a whole-body dose of 100 rad has absorbed one joule of energy in each kg of body tissue (i.e., 1 Gy).

Conversions from the SI units to other units are as follows:

1 Gy = 100 rad

1 mGy = 100 mrad



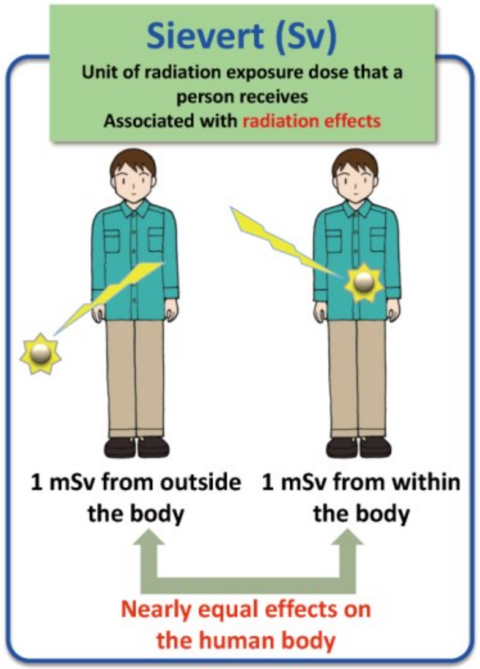
Pair production

Equivalent dose (symbol H_T) is a dose quantity calculated for individual organs (index T – tissue). The equivalent dose is based on the absorbed dose to an organ, adjusted to account for the effectiveness of the type of radiation.

An equivalent dose is given the symbol H_T.

The SI unit of HT is the ***Sievert*** (*Sv*)

1 Sievert represents the equivalent biological effect of depositing a 1 joule of gamma ray energy in a 1 kilogram of human tissue.



1 Sievert is a large amount of equivalent dose. A person who has absorbed a whole-body dose of 1 Sv has absorbed one joule of energy in each kg of body tissue (in case of gamma rays).

1 *rem* (roentgen equivalent man) is used .

Conversions from the SI units to other units are as follows: 1 Sv = 100 rem

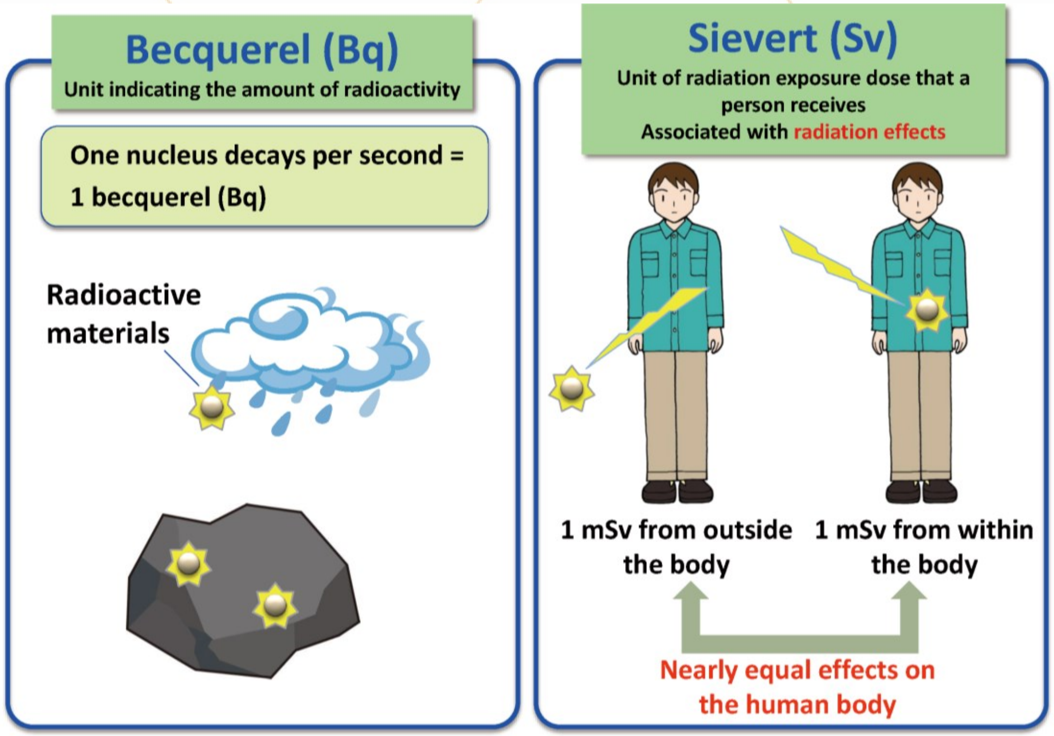
The collective effective dose is defined as the sum of all individual effective doses in a group of people over the time period or during the operation being considered due to ionizing radiation. The collective dose is given the symbol S.

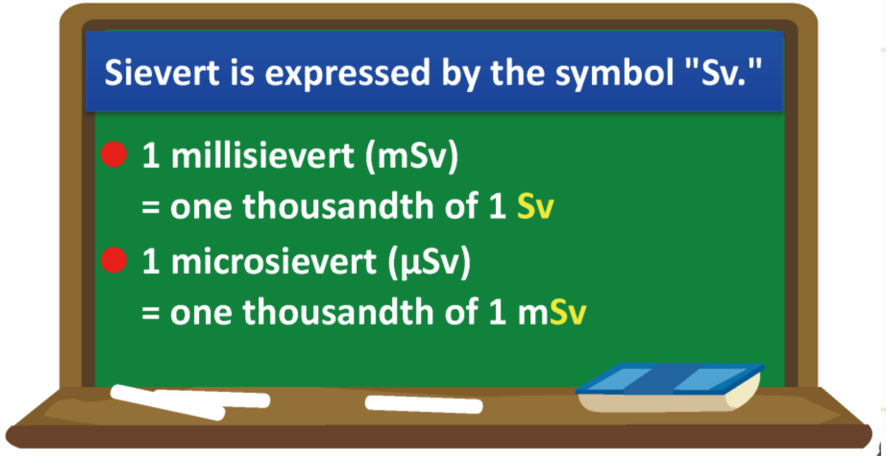
The unit of the collective effective dose is joule per kilogram ($J.kg^{-1}$) or ***man sievert*** (***man Sv***).

The collective dose can be obtained by the product of the average individual dose with the number of people in the group.

$$S = \sum_i E_i \; N_i$$

- E_i is the average effective dose for a subgroup i.
- N_i is the number of individuals in the subgroup i.



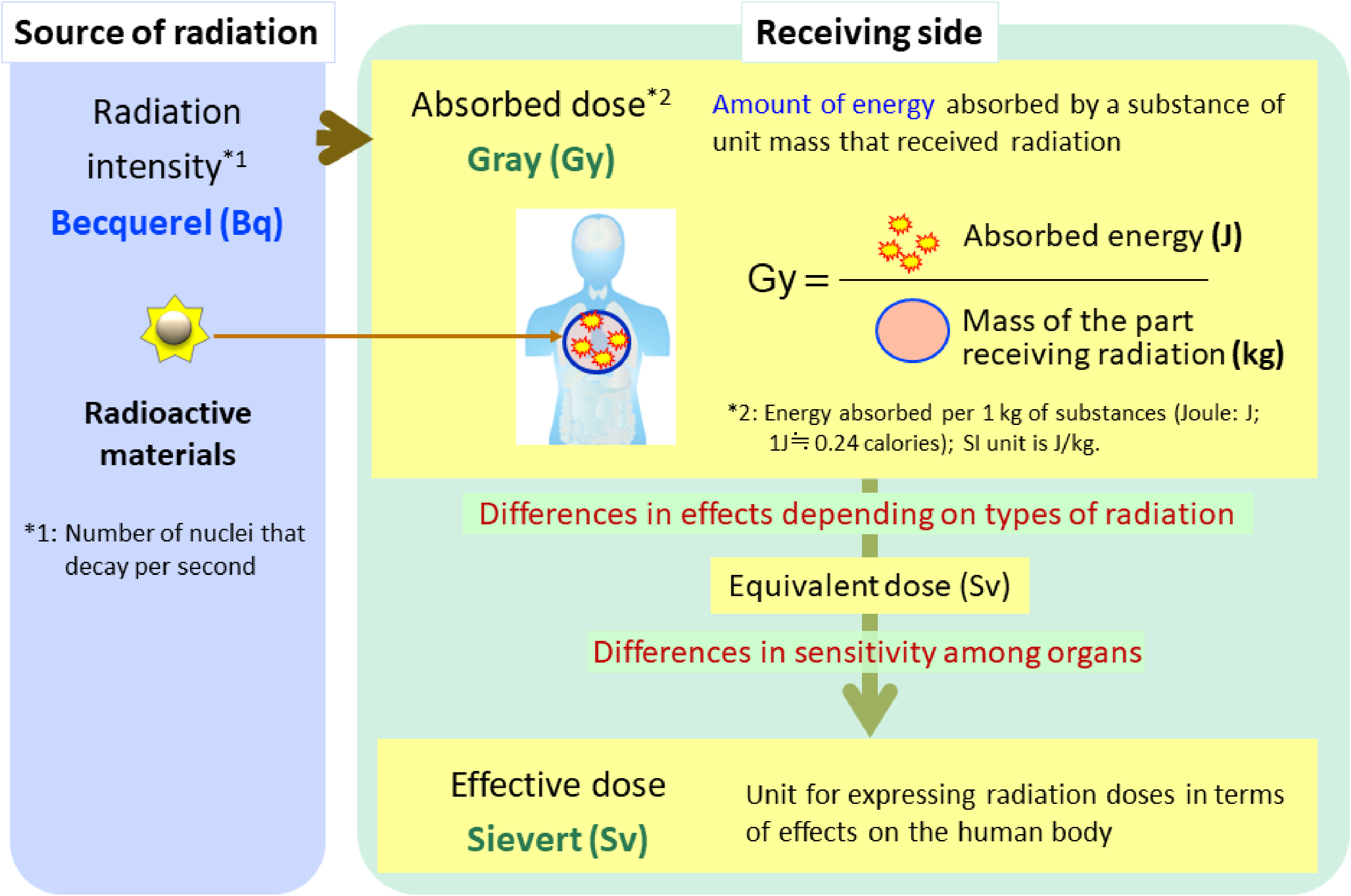


Becquerel and *sievert* are the most common units of radiation.

Becquerel is a *unit of radioactivity* and focuses on where radiation comes from. It is used to express the amount of radioactive material contained in soil, foods, tap water, etc. The higher the value expressed in becquerels, the larger the radiation being emitted.

Sievert is a *unit of radiation* exposure dose that a person receives and is used with regard to what is exposed to radiation, i.e. the human body. The larger the value expressed in sieverts, the larger the effects of radiation to which the human body is exposed

Gray is a *unit of absorbed dose*, defined as the absorption of one joule of radiation energy per kilogram of matter.



Units of radiation can be broadly divided into units for sources of radiation and units for the receiving side.

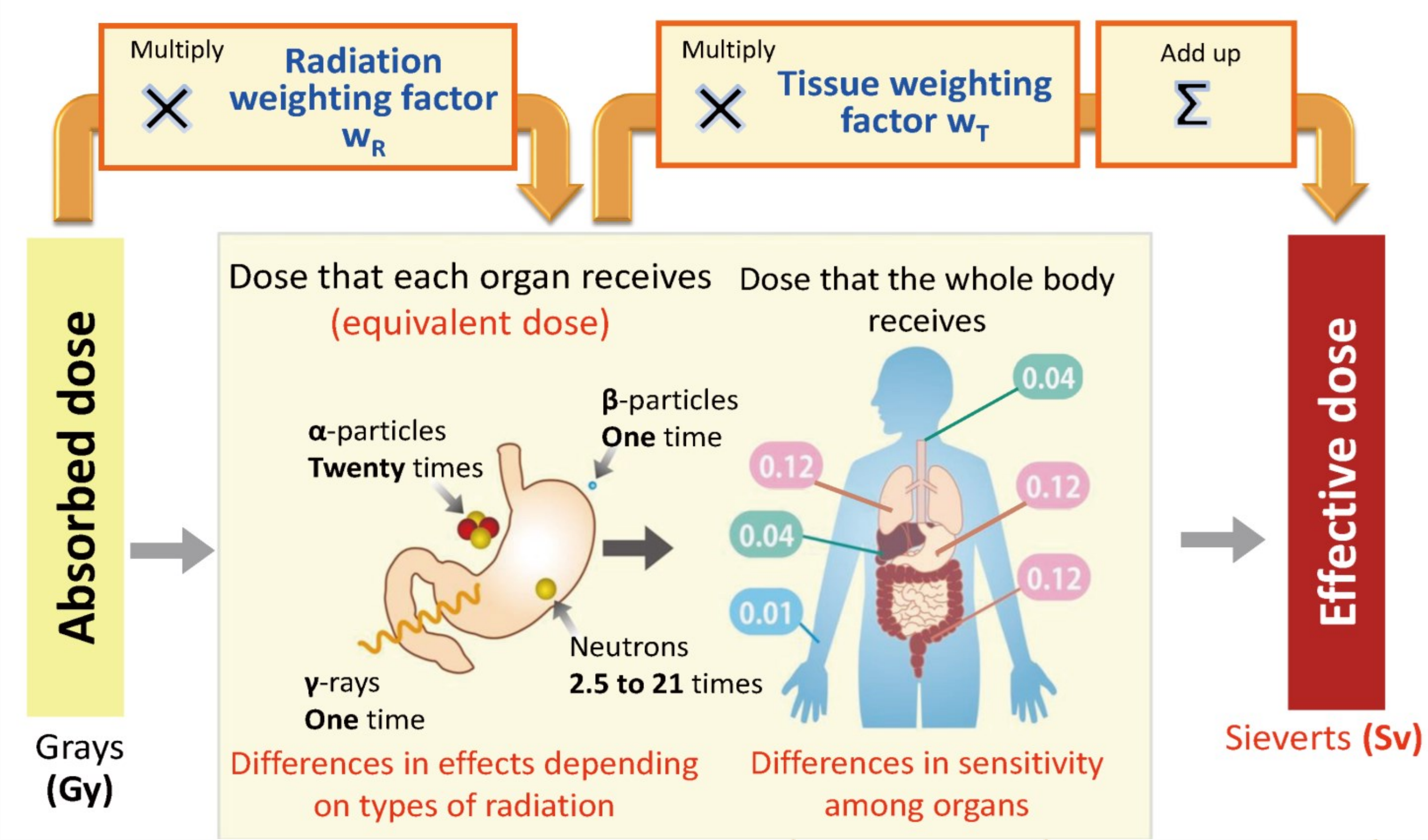
Becquerel, a unit of radioactivity, is used for sources of radiation.

Units for the receiving side are gray and sievert.

When radiation passes through something, its energy is absorbed there.

Gray is a unit for indicating the absorbed dose.

The extent of effects on the human body varies depending on the types and energy quantities of radiation even if the absorbed doses are the same. Doses weighting health effects of respective types of radiation are equivalent doses (expressed in sieverts). The effective dose (expressed in sieverts) was developed for exposure management in radiological protection. In contrast to the equivalent dose, the effective dose weights differences in sensitivity among organs and tissues and sums them up to express the radiation effects on the whole body.



The tissue weighting factors summate to 1.

The effective dose can be considered as the weighted average of the equivalent doses of all organs and tissues.

Effective doses can be calculated similarly for both internal and external exposures.

To calculate the *effective dose* that expresses the effects of radiation exposure on the whole body, it is necessary to first determine the absorbed doses of individual tissues and organs exposed. The equivalent dose (expressed in sieverts) is obtained by multiplying the absorbed doses of individual tissues and organs by their respective radiation weighting factors (W_R) for taking into account the types of radiation.

The value of the radiation weighting factor is larger for the types of radiation having larger effects on the human body (α-particles: 20; β-particles and γ-rays: 1).

Once the equivalent doses for individual tissues and organs exposed to radiation are determined, they are then multiplied by the respective tissue weighting factors (W_T) for taking into account differences in sensitivity among organs, and the products are summed. The tissue weighting factors are for weighting the radiation sensitivity of individual tissues and organs.

Any organ or tissue where radiation is likely to induce fatal cancer is given a higher factor.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-03-04.html

Equivalent dose (**Sv**) = Radiation weighting factor w_R × Absorbed dose (**Gy**)

Type of radiation	Tissue weighting factor w_R
γ-rays, X-rays, β-particles	**1**
Proton beams	**2**
α-particles, heavy ions	**20**
Neutron beams	**2.5～21**

Effective dose (Sv) = Σ (Tissue weighting factor w_T × Equivalent dose)

Tissue	Tissue weighting factor w_T
Red bone marrow, colon, lungs, stomach, breasts	**0.12**
Gonad	**0.08**
Bladder, esophagus, liver, thyroid	**0.04**
Bone surface, brain, salivary gland, skin	**0.01**
Total of the remaining tissues	**0.12**

Sv: sieverts; Gy: grays

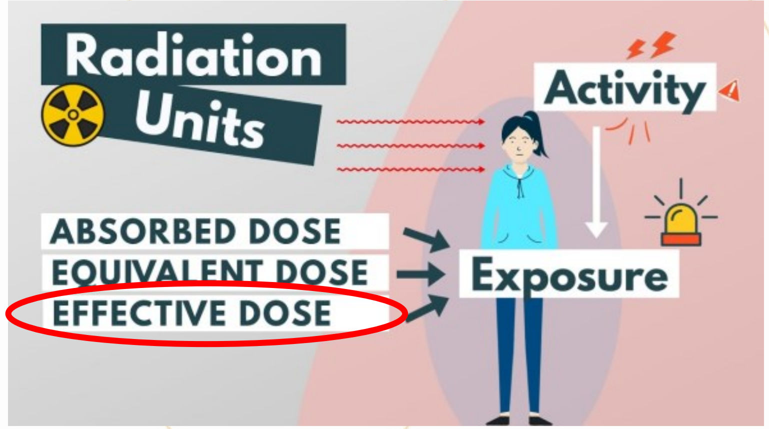
Source: 2007 Recommendations of the ICRP

Recommendations issued by the International Commission on Radiological Protection (ICRP) claimed *weighting factors* and *tissue weighting factors*.

α-particles have 20 times larger effects on the human body than *γ*-rays and β-particles with the same absorbed doses.

Neutron beams are also given high radiation weighting factors and are expected to have 2.5 to 21 times larger effects on the human body than *γ*-rays and β-particles depending on the energy quantities.

ICRP
International Commission on Radiological Protection



The effective dose can be expressed as:

$$E = \sum_T w_T H_T$$

H_T is the equivalent dose averaged over the tissue or organ T due to the incident radiation

w_T is the tissue weighting factor

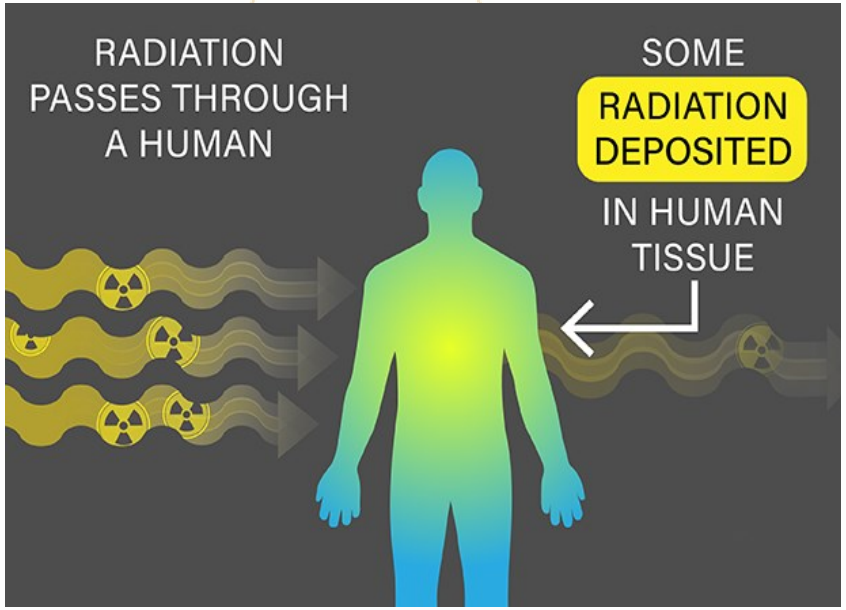
Stochastic effects of ionizing radiation occur by chance, generally occurring without a threshold level of dose. The probability of occurrence of stochastic effects is proportional to the dose, but the severity of the effect is independent of the dose received. The biological effects of radiation on people can be grouped into somatic and hereditary effects. Somatic effects are those experienced by the exposed person, and hereditary effects are those experienced by the offspring of the individual exposed. Cancer risk is usually mentioned as the main stochastic effect of ionizing radiation, but also hereditary disorders are stochastic effects.

The **effective dose** is defined as the doubly weighted sum of absorbed doses in all the organs and tissues of the body.

It is important whether a person is exposed partially or completely, and it is important whether a person is exposed to gamma rays or another type of radiation. Effective dose allows for determining stochastic biological consequences of all types of radiation.

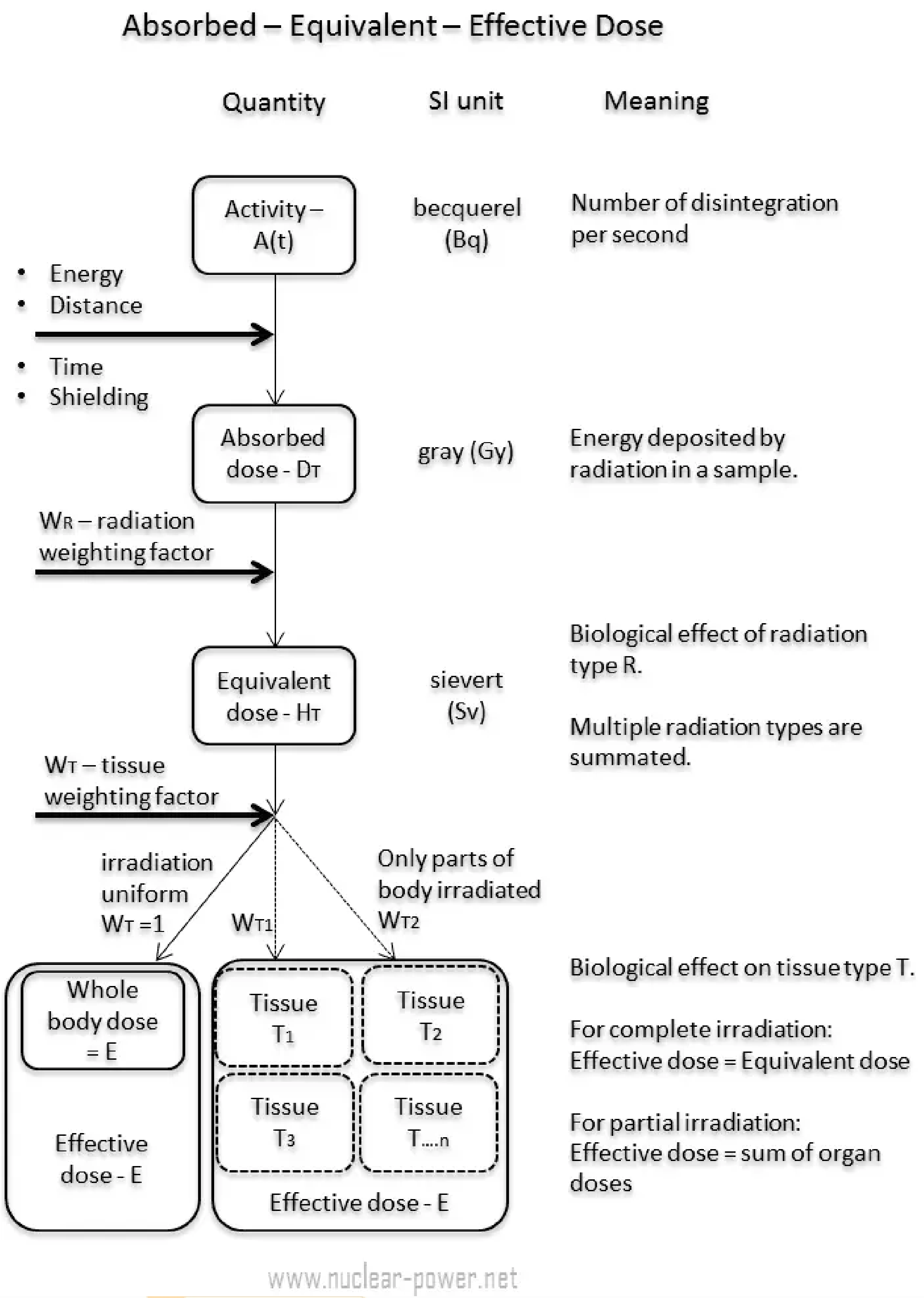
Dose limits are set in terms of effective dose and apply to the individual for radiological protection purposes, including the assessment of risk in general terms.

Radiation is all around us

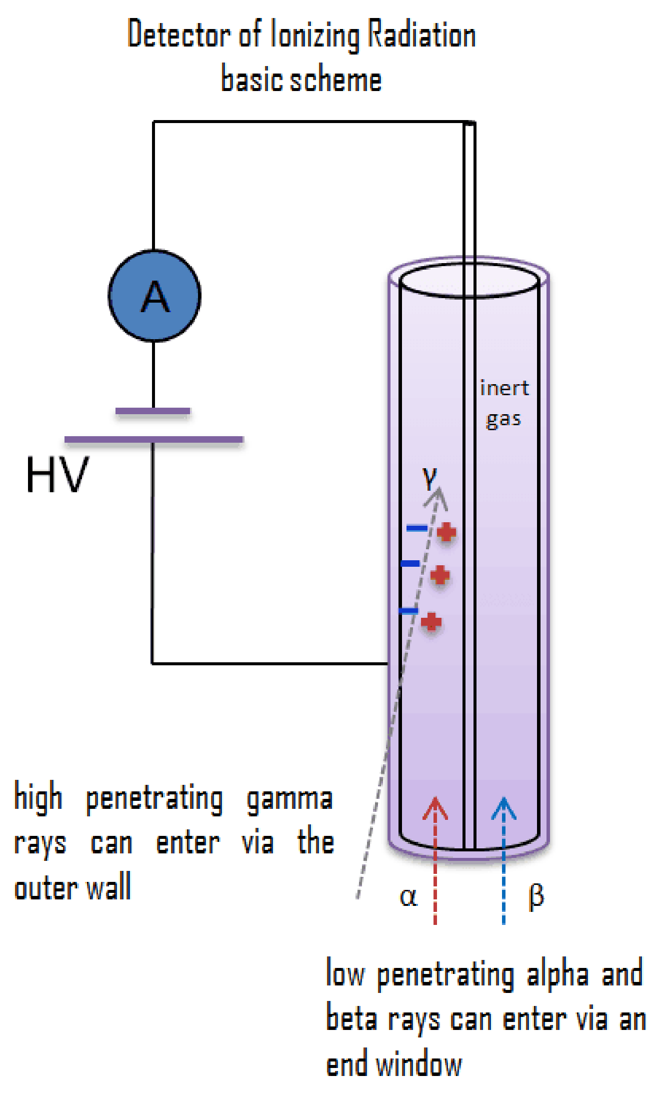


0.05 μGy – Sleeping next to someone
0.09 μGy – Living within 30 miles of a nuclear power plant for a year
0.1 μGy – Eating one banana
0.3 μGy – Living within 50 miles of a coal power plant for a year
10 μGy – Average daily dose received from natural background
20 μGy – Chest X-ray
40 μGy – A 5-hour airplane flight
600 μGy – Mammogram
1 000 μGy – Dose limit for individual, total effective dose per annum
3 650 μGy – Average yearly dose received from natural background
5 800 μGy – Chest CT scan
10 000 μGy – Average yearly dose received from a natural background in Ramsar, Iran
20 000 μGy – Single full-body CT scan
175 000 μGy – Annual dose from natural radiation on a monazite (Guarapari, Brazil).
5 000 000 μGy – Dose that kills humans with a 50% risk (received over a **short duration)**

From biological consequences, it is very important to distinguish between doses received over short and extended periods. An "acute dose" occurs over a short and finite period, while a "chronic dose" is a dose that continues for an extended period so that a dose rate better describes it.
High doses tend to kill cells, while low doses tend to damage or change them.
Low doses spread out over long periods don't cause an immediate problem to any body organ. The effects of low radiation doses occur at the cell level, and the results may not be observed for many years.



	SI Units	Other units
Radioactivity	becquerel (Bq)	curie (Ci)
Absorbed Dose	gray (Gy)	rad
Equivalent Dose	sievert (sv)	rem
Exposure	coulomb/kilogram (C/kg)	roentgen (R)



Counter. The activity or intensity of radiation is measured in counts per second (cps). The best-known counter is the Geiger-Müller counter. In radiation counters, the generated signal from the incident radiation is created by counting the number of interactions occurring at the sensitive volume of the detector.

Radiation Spectrometer. Spectrometers are devices designed to measure the spectral power distribution of a source, and the incident radiation generates a signal that allows determining the energy of the incident particle.

Dosimeter. A radiation dosimeter is a device that measures exposure to ionizing radiation. Dosimeters usually record a dose, which is then absorbed radiation energy, measured in grays (Gy), of the equivalent dose, measured in sieverts (Sv). A personal dosimeter is a dosimeter, that is worn at the surface of the body by the person being monitored and records the radiation dose received.

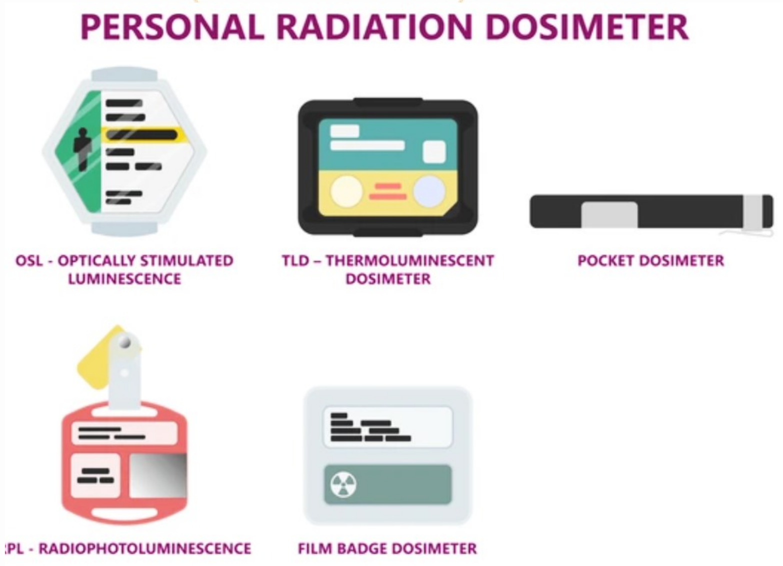
https://www.radiation-dosimetry.org/page/28/?lang=en

Dosimetry is the measurement and calculation of the absorbed dose of ionizing radiation in matter and the assessment of its potential biological effects. It is a crucial field in radiation safety, used in various industries like healthcare (radiology, radiotherapy), nuclear power, and environmental monitoring.

There are various types of dosimeters used to measure radiation exposure, each with its own characteristics and applications. Here are a few common types:

- **Thermo-luminescent Dosimeters (TLDs)**
- **Optically Stimulated Luminescence Dosimeters (OSLDs)**
- **Film Badge Dosimeters**
- **Pocket Ionization Chambers**
- **Electronic Personal Dosimeters (EPDs**
- **Solid-State Dosimeters**

Each type of dosimeter has its advantages and limitations in terms of sensitivity, accuracy, cost, and ease of use, making them suitable for different applications and environments.



Radiation Dosimeters: Thermal Luminescent Dosimeter (TLD)

The thermal luminescent dosimeter (TLD) is a light free device, usually containing a crystalline form of lithium fluoride that functions as the sensing material of the TLD. Ionizing radiation causes some of the electrons in the crystalline lattice structure of the lithium fluoride molecule to absorb energy, exciting them to higher energy levels or bands.

The electrons can return to their original or normal state with the emission of energy in the form of visible light. The analyzer then measures the amount of ionizing radiation that the TLD has been exposed and develops a glow curve representing the exposure received by the individual TLD. This device measures exposures as low as 1.3 x 10^{-6} C/kg (5 mR) accurately and may be used for up to three months. TLDs may only be read once because the read-out process destroys the stored information.

Radiation Dosimeters: Pocket Ionization Chamber Dosimeter

The pocket ionization chamber, which resembles an ordinary fountain pen, is considered to be the most sensitive type of personnel dosimeter. There are two types of pocket dosimeters: self- reading and non-self-reading. The pocket ionization chamber contains two electrodes, one positively charged and the other negatively charged. When exposed to gamma and X-radiation, the air surrounding the pre-charged central or positive electrode becomes ionized. Subsequently, the negative ions in the air are attracted to the positively charged central electrode, neutralizing its charge. This has the effect of discharging the mechanism in direct proportion to the amount of radiation that the device was exposed to. These devices are expensive, costing as much as $150 per unit, and if not read out every day, may give an inaccurate reading. The use of this type of radiation dosimeter is uncommon in diagnostic imaging.

https://www.medical-professionals.com/en/comparing-radiation-dosimeters/

Radiation Dosimeters: Optically Stimulated Luminescence (OSL) Dosimeter

The second most sensitive between radiation dosimeters is the optically stimulated luminescence dosimeter or OSL dosimeter. This is the most common type of personnel dosimeter used in the monitoring of occupational radiation exposure in diagnostic radiology today. This type of dosimeter is light-weight, durable, and easy to carry. It contains an aluminum oxide detector and is read out by using a laser light at selected frequencies. When the laser light is incident on the sensing material, it becomes luminescent in proportion to the amount of radiation exposure it received. An OSL dosimeter can be worn for up to one year, but they are usually worn for only 1-3 months before being read out. These devices provide an accurate reading as low as 10 µSv for X-ray and gamma ray photons with energies ranging from 5 keV to greater than 40 MeV.

Radiation Dosimeters: Digital Ionization Personnel Dosimeters

Compact professional personnel digital ionization dosimeters have been developed and designed to monitor and measure the personal dose equivalent rate from both gamma and X-rays in a range spanning from 20 keV to 10 MeV. This type of radiation dosimeter, which is small in size and similar in appearance to a flash drive, provides immediate measurement of radiation exposure. It allows for manual or automatic recording up to 4000 events of dose rate change, acute dose levels, and the time and levels when present threshold values were exceeded. The dosimeter communicates with a PC via a USB channel with simultaneous battery charging. Also, it contains a Personal Dose Tracker software that enables analysis of dose readings and report generation. Some of these reports include, but are not limited to, a radiation exposure summary, a history detail report, and a report on who has not read this device. Some contain a GPS, a global positioning system, or microchip that also adds data concerning the location of exposure events.

Geiger-Müller Counter

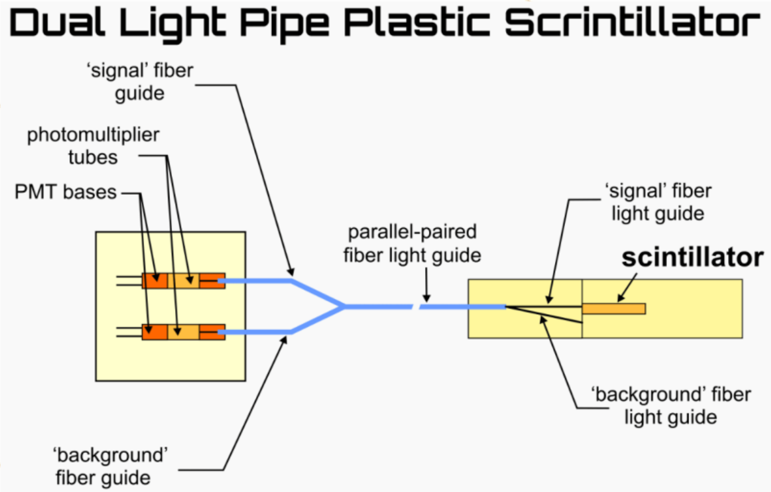
A basic gaseous ionization detector consists of a chamber filled with inert gas that can be ionized. The center wire is the positive electrode (anode), and the outer cylinder is the negative electrode (cathode), so that (negative) electrons are attracted to the center wire. Positive ions are attracted to the outer cylinder. The anode is at a positive voltage for the detector wall. As ionizing radiation enters the gas between the electrodes, a finite number of ion pairs are formed. Under the influence of the electric field, the positive ions will move toward the negatively charged electrode (outer cylinder), and the negative ions (electrons) will migrate toward the positive electrode (central wire). Collecting these ions will produce a charge on the electrodes and an electrical pulse across the detection circuit.

Plastic Scintillators

Plastic scintillation dosimeters emit light when irradiated. Scintillation may be read out by a photodetector and correlated with absorbed dose. Plastic scintillators have several desirable qualities including near tissue equivalency, small size limited by the ability to detect small amounts of light, and energy independence in the MV range. These qualities make scintillators valuable detectors with applications in small field dosimetry, high resolution detector arrays (IMRT QA), and, because the collision stopping power ratio of plastic is similar to water, electron measurements.

While plastic scintillators function well for the detection of gamma and beta particles, other scintillation materials are also commonly used.

- NaI(Tl): Low energy (up to about 360keV) photon detection.
- ZnS: Detection of alpha particles.



Neutron Detectors

Bubble detectors consist of a clear plastic tube filled with a gel polymer. When fast neutrons are incident upon the polymer, they superheat the polymer creating bubbles. These bubbles remain suspended in the gel and may be counted to determine neutron fluence or absorbed dose. Bubble chambers are able to measure both fast and, with the addition of a neutron absorber such as chlorine, thermal neutrons. These features make bubble detectors well suited for in-vault neutron measurements.

Dose Measurement

1. Bubble detector cap is unscrewed reducing the chamber pressure and allowing measurement.
2. Detector is exposed to neutrons. Neutron interactions superheat the polymer forming bubbles.
3. Bubbles are counted either by eye or optically. The number of bubbles is correlated with fluence or absorbed dose.
4. Bubble detector is reset by screwing down cap causing the internal pressure to increase.

Advantages

- Useful for in-vault measurements
- Good photon rejection
- Suitable for high dose rate
- No down time
- Small size
- Usable for personnel dosimetry
- Available in various energy ranges from thermal to fast
- Reusable

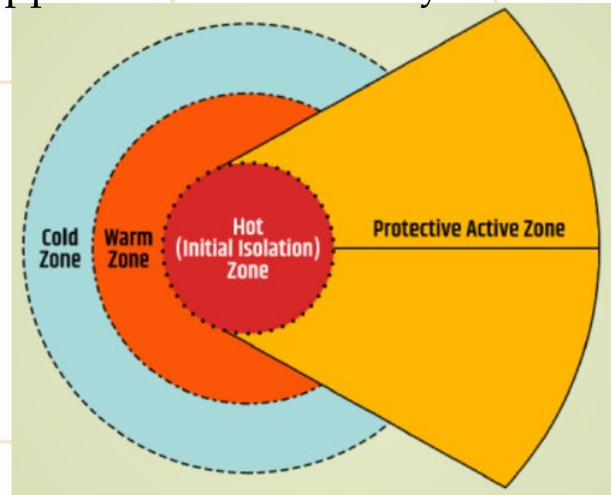
Disadvantages

- May have strong temperature dependence (5% per C).
- This can be reduced by adding volatile liquid to the chamber whose vapor pressure compensates for temperature sensitivity.
- Bubble overlap makes readout difficult in high dose measurements.
- May lose sensitivity over time due to medium degradation.

Dosimeters are most commonly used by professionals in industrial and medical applications and also by radiation emergency workers.

Typical applications where dosimeters are used are

- ✓ Nuclear power;
- ✓ Radiology;
- ✓ Oncology;
- ✓ Nuclear medicine;
- ✓ Construction;
- ✓ Maritime;
- ✓ Public safety.



Workers use personal radiation dosimeters to determine increasing radiation dose exposure. Several dosimeters may warn about the use of extremely harmful doses of radiation when others are parts of the increased radiation dose regulation and protection program.

There are three main regulation zones when processing the radiation incident:

The **cold zone** is a pollution-free area that encourages operations and critical planning to eliminate radiation from the emergency incident. The radiation level is at the background dose in this area.

The **warm zone** is the depollution area and is set up between the cold and hot zones.

The **hot zone** surrounds the radiation scene right away. Proper personal protective equipment (PPE) is strictly required here.

Personal radiation dosimeters are used by emergency professionals in these regulating areas and will be alerted when radiation levels are hazardous.

https://megadepot.com/resource/what-is-a-dosimeter-and-how-does-it-work

Sources of Natural Background Radiation:

- Cosmic Radiation
- Terrestrial Radiation
- Internal Radiation

Three main sources of Cosmic Radiation :

Solar radiation - high-energy particles (predominantly protons) emitted by the sun.

Galactic cosmic radiation - high-energy particles originating outside the solar system (galaxy).

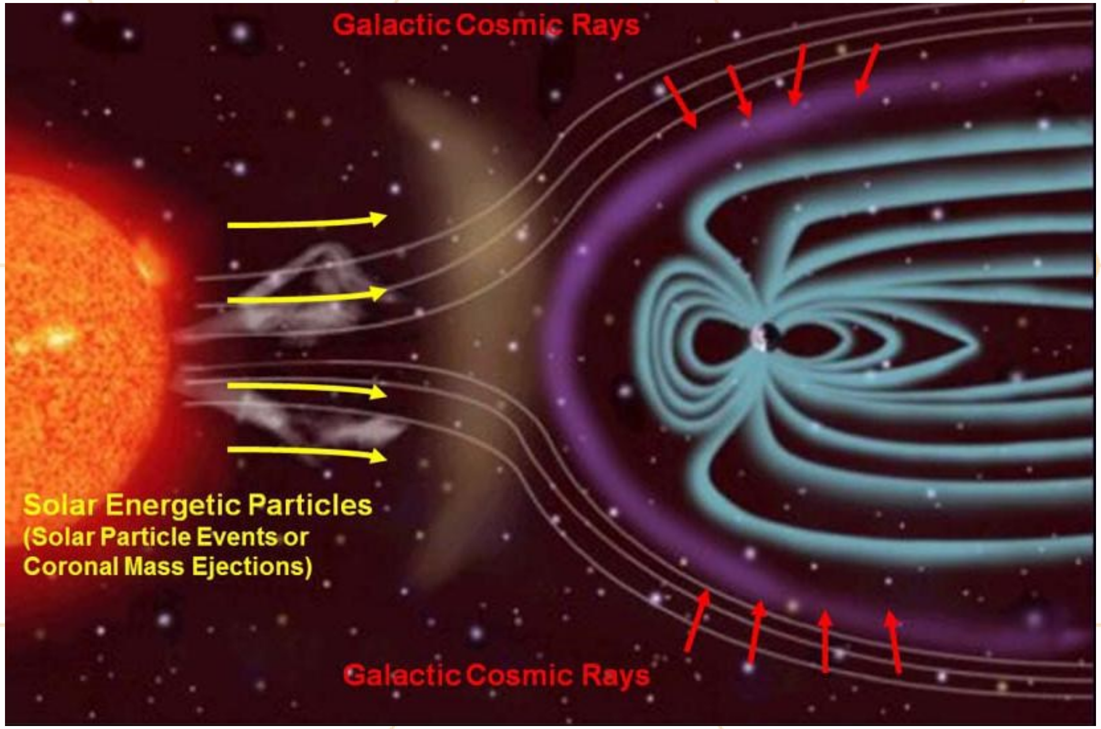
Radiation from Earth's Radiation Belts (van Allen belts)

Van Allen radiation belts are zones of high-energy particles (especially protons) trapped by Earth's magnetic field.

The annual cosmic ray dose at sea level is around 0.25-0.35 mSv

If you live at higher elevations or are a frequent airline passenger, this exposure can be significantly higher since the atmosphere is thinner here. The effects of the Earth's magnetic field also determine the dose of cosmic radiation.

The ground level dose rate is about 0.04 μSv/h, but at the maximum flight altitude (10 km) it is about 1 μSv/h.



Sources of Natural Background Radiation:

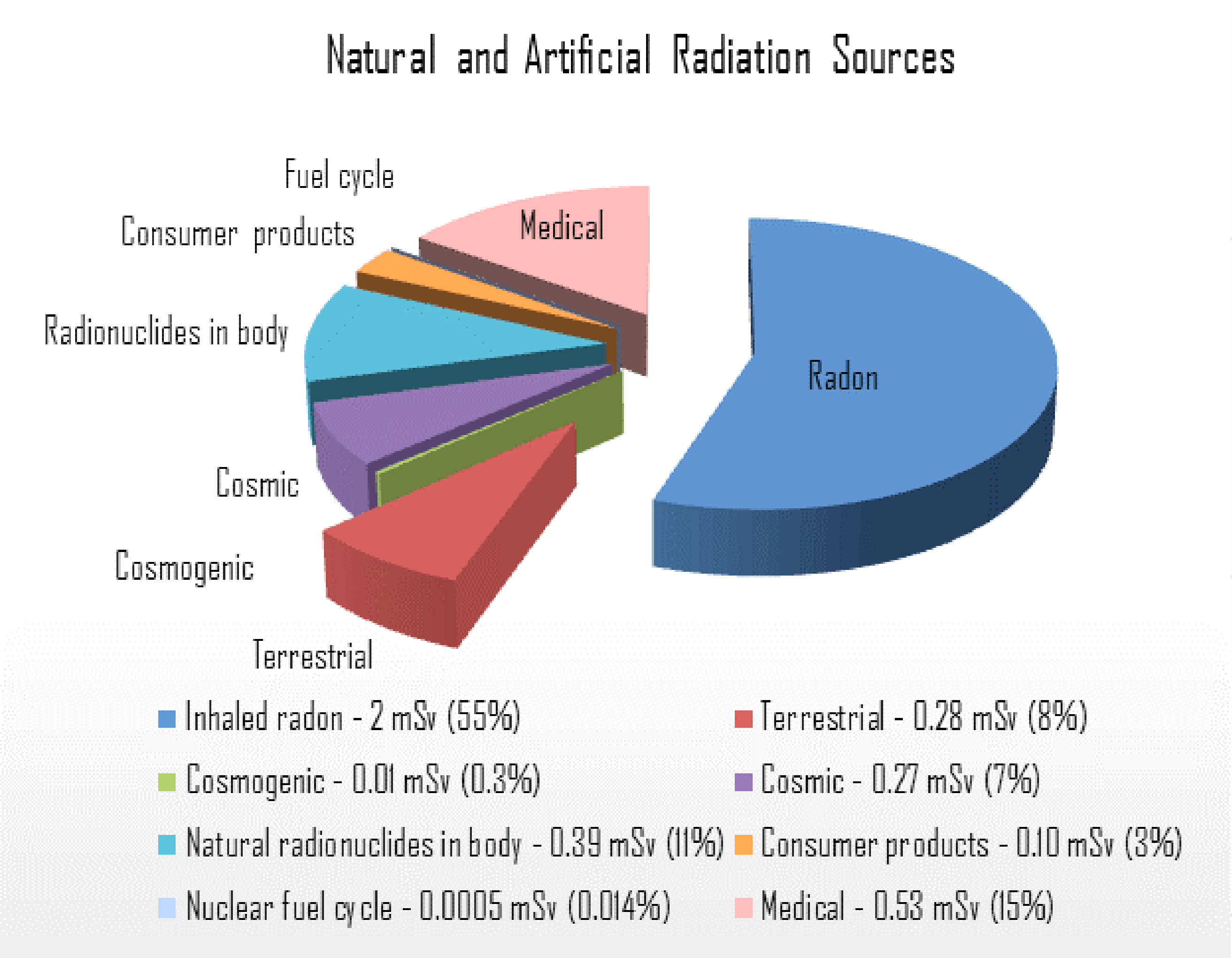
- Cosmic Radiation
- Terrestrial Radiation
- Internal Radiation

Main sources of terrestrial radiation are rocks, soil and water radiation sources.

The annual terrestrial radiation dose is around 0.20-0.35 mSv

(except radon exposure)

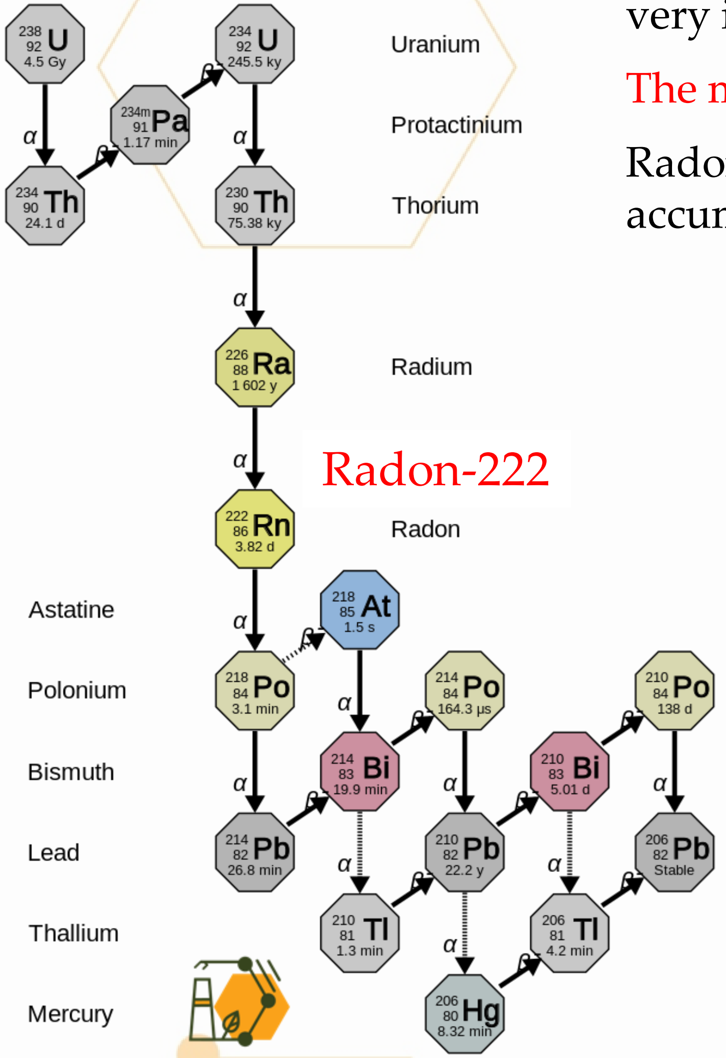
The major isotopes for terrestrial radiation are uranium and the decay products of uranium (thorium, radium, and radon).



https://www.radiation-dosimetry.org/what-is-natural-neutron-background-definition/

Sources of Natural Background Radiation:

- Cosmic Radiation
- Terrestrial Radiation
- Internal Radiation



Radon is a colorless, odorless noble gas, occurring naturally as the decay product of radium.

All isotopes of radon are radioactive, but the two radon isotopes radon-222 and radon-220 are very important from radiation protection point of view.

The main problem is that radon is a gas

Radon-222 has a half-life of only 3.8 days. Radon gas seeps continuously from bedrock and accumulate (because of its high density) in poorly ventilated houses.

Radon is usually the largest natural source of radiation contributing to the exposure of members of the public, *accounting for half the total exposure from all sources*.

The health risk due to exposure to radon comes principally from the inhalation of the short-lived decay products (Pb-210 and Po-210) and the resulting alpha particle irradiation of the bronchi and the lungs. (As long as these isotopes are outside the body, only the gamma radiation will be able to give a dose)

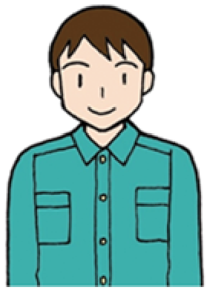
The average annual radiation dose to a person from radon is about 2 mSv/year and it may vary over many orders of magnitude from place to place.

Radon can accumulate especially, due to its high density, in low areas such as basements and crawl spaces. Radon can also occur in ground water – for example, in some spring waters and hot springs.

Sources of Natural Background Radiation:

- Cosmic Radiation
- Terrestrial Radiation
- Internal Radiation

Radioactive materials in the body



When body weight is 60kg		
Potassium-40	※1	4,000Bq
Carbon-14	※2	2,500Bq
Rubidium-87	※1	500Bq
Tritium	※2	100Bq
Lead and polonium	※3	20Bq

※1 Nuclides originating from the Earth
※2 Nuclides derived from N-14 originating from cosmic rays
※3 Nuclides of the uranium series originating from the Earth

Main sources of internal radiation are radioactive isotopes inside bodies from birth.

These isotopes are potassium-40, carbon-14, and the isotopes of uranium and thorium.

The average annual radiation dose to a person from internal radioactive materials other than radon is about 0.3 mSv/year, which:
0.2 mSv/year comes from potassium-40,
0.12 mSv/year comes from the uranium and thorium series,
12 µSv/year comes from carbon-14.

The most important isotope with regard to dose is potassium-40.

The dominant component of inhalation exposure is the short-lived decay products of radon.

A 60-kg individual contains about 120 g of potassium (0.2%), mostly located in muscles. The concentration of potassium-40 is nearly stable in all individuals at a level of about 60 Bq/kg (4000 Bq in total), which corresponds to the annual effective dose of 0.2 mSv.

The transfer of potassium ions through nerve cell membranes is necessary for normal nerve transmission. Potassium-40 is a radioactive isotope of potassium that has a very long half-life of 1.251×10^9 years and undergoes both types of beta decay.

Banana equivalent dose (BED) is a dose quantity of ionizing radiation exposure (0.1 µSv).

Bananas contain significantly high potassium concentrations, which are vital for the functioning of all living cells.

Two groups exposed to manufactured radiation sources.

Public exposure is the exposure of individual members of the public and the population in general

Medical Exposures

- Diagnostic X-rays
- Nuclear medicine procedures

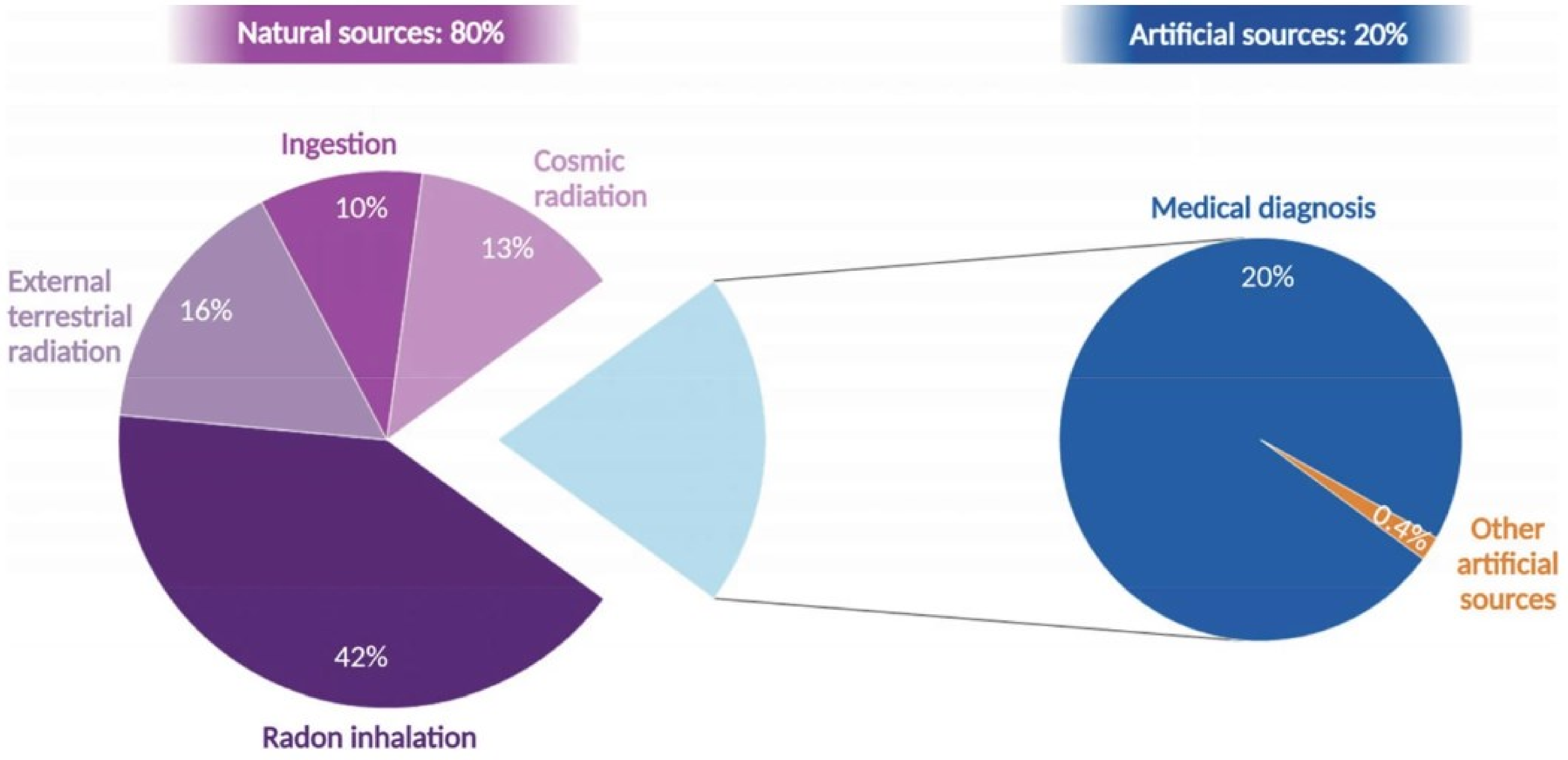
Consumer Products

- Building and road construction materials
- Smoking cigarettes (polonium-210)
- Combustible fuels, including gas and coal
- X-ray security systems
- Televisions
- Smoke detectors
- Lantern mantles

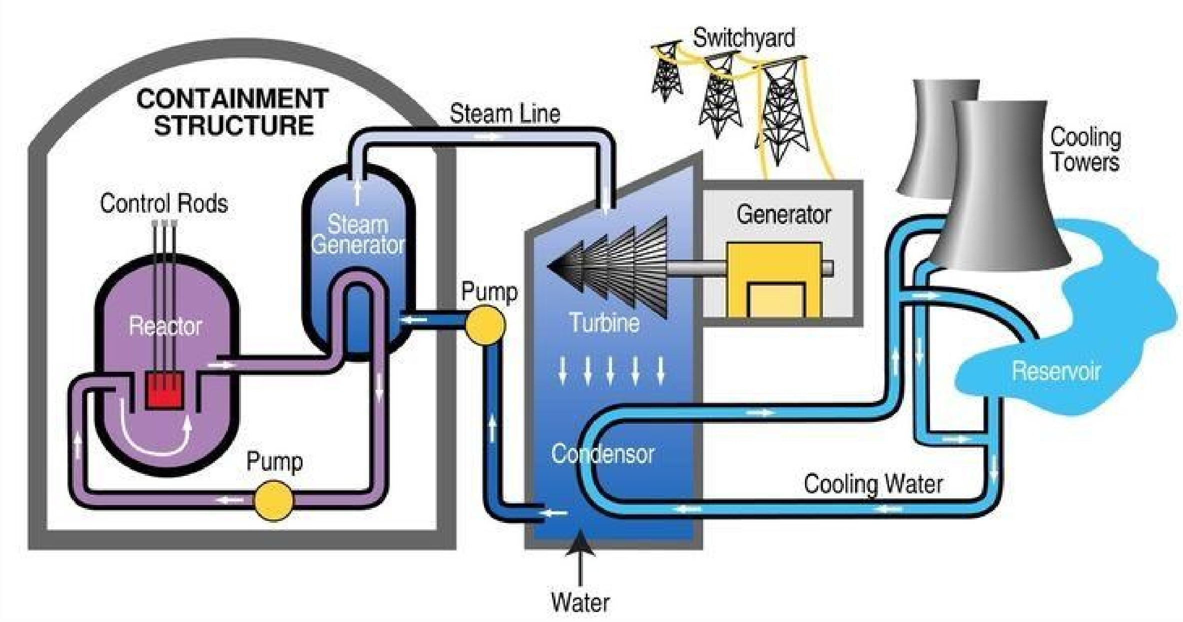
Occupational radiation exposure is the exposure of workers in situations where their exposure is directly related to their work

- Fuel cycle facilities
- Industrial radiography
- Radiology departments (medical)
- Nuclear medicine departments
- Radiation oncology departments
- Nuclear power plants
- Government and university research laboratories

Ionizing radiation has many industrial and medical uses. Manufactured sources include medical uses of radiation, residues from nuclear tests, industrial uses of radiation, television, and numerous other radiation-producing devices.



https://link.springer.com/chapter/10.1007/978-3-031-18810-7_2



A nuclear power plant is a thermal power plant in which a nuclear reactor generates heat, which is used to generate steam, which drives a steam turbine connected to a generator that produces electricity.

https://personal.ems.psu.edu/~pisupati/ACSOutreach/Nuclear.html

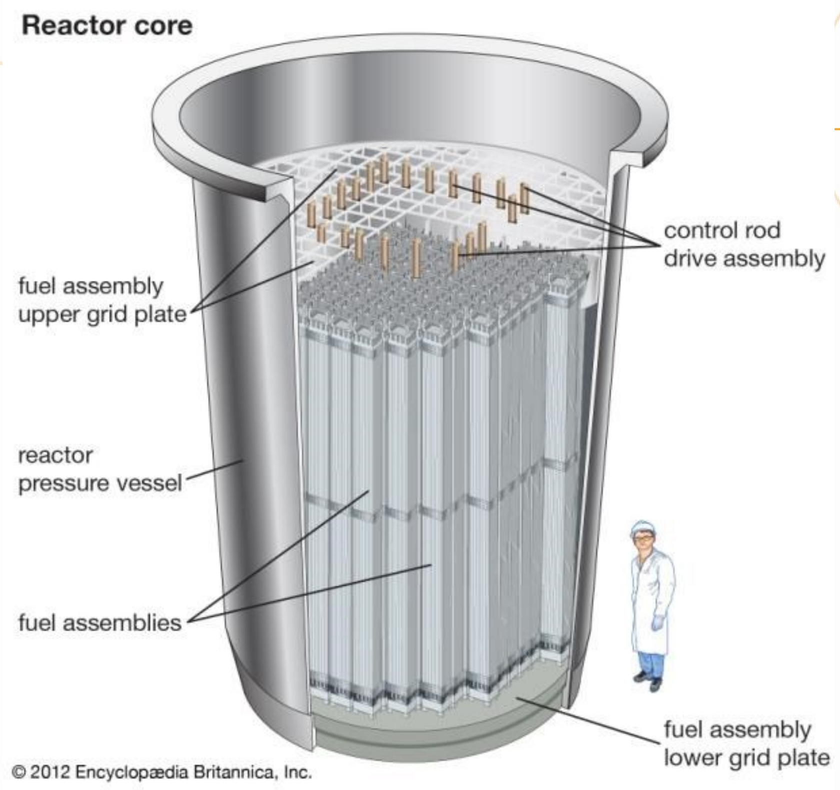
The nuclear power plants comprises two major parts:
The nuclear island and the conventional (turbine) island.

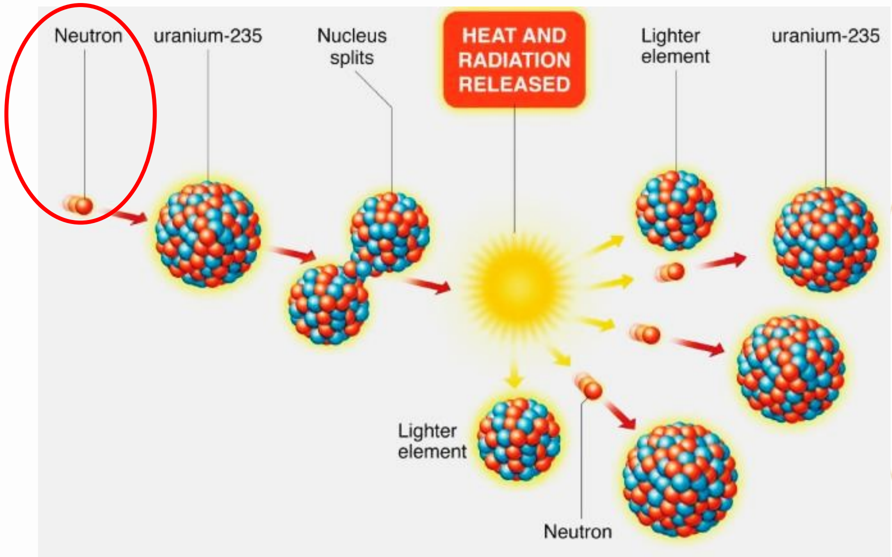
Nuclear island

A nuclear reactor contains the *reactor core and the control systems*.
Reactor *coolant pumps* ensure circulation of the primary coolant.
Pressurizer is used to control the pressure of the primary coolant.
In steam generators, heat is exchanged between the primary circuit and the secondary circuit; Primary piping; Safety systems; Containment building

Conventional island

Steam turbine. A steam turbine is a device that extracts thermal energy from pressurized steam and uses it to do mechanical work on a rotating output shaft.
Generator. A generator is a device that converts the mechanical energy of the steam turbine to electrical energy.
Condenser. A condenser is a heat exchanger used to condense steam from the last stage of the turbine.
Condensate-feedwater system. Condensate-Feedwater Systems have two significant functions: to supply adequate high-quality water (condensate) to the steam generator and heat the water (condensate) to a temperature close to saturation.
Moisture separator reheater. The moisture separator reheaters are usually installed between the high-pressure turbine outlet and the low-pressure turbine inlets to remove the moisture from the high-pressure turbine exhaust steam and reheat this steam.
Cooling system and cooling towers.





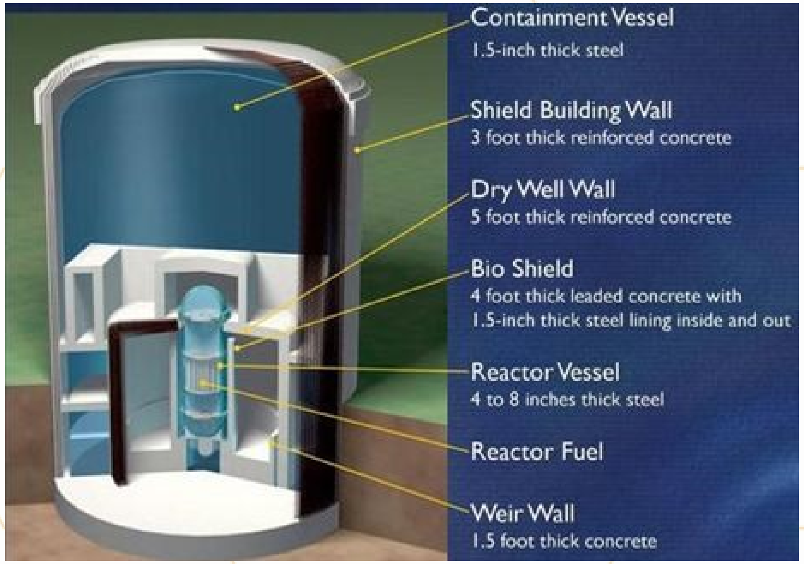
Any nuclear reactor that produces power via the fission of uranium (U-235) or plutonium (Pu-239) by bombardment with neutrons must have at least five components:

nuclear fuel consisting of fissionable material uranium-235 and plutonium-239

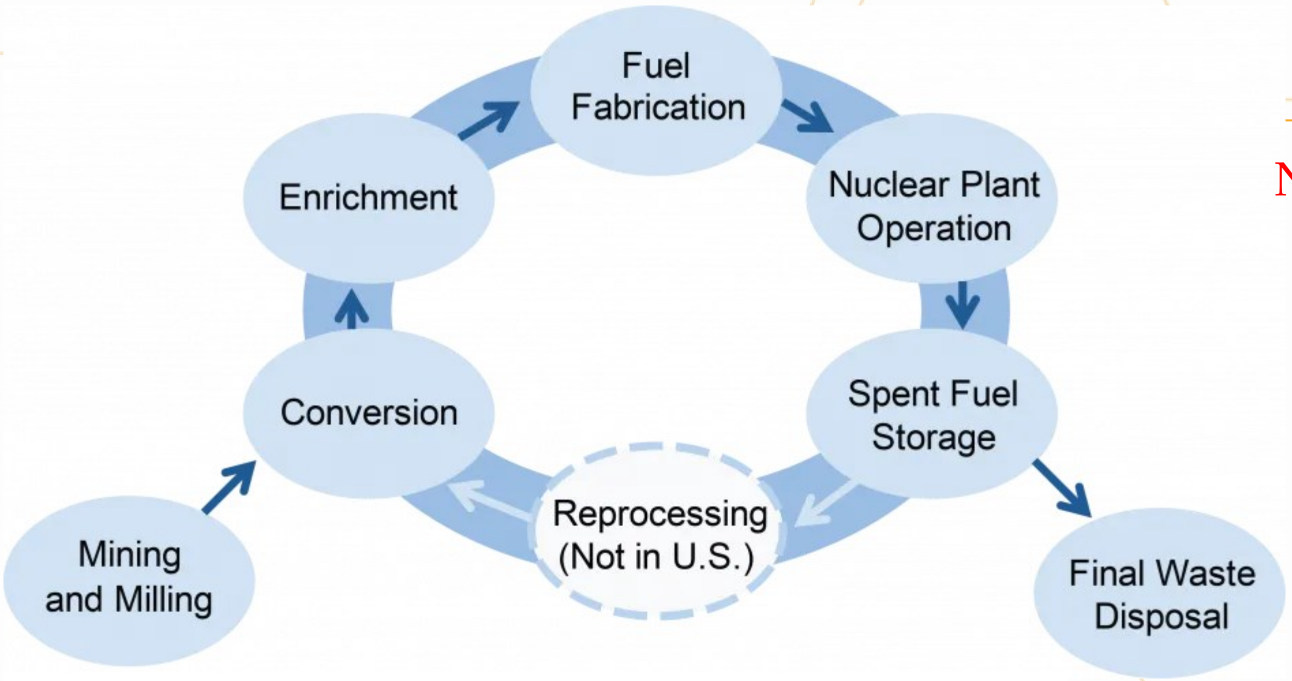
a nuclear moderator - slows down neutrons for fission initiates

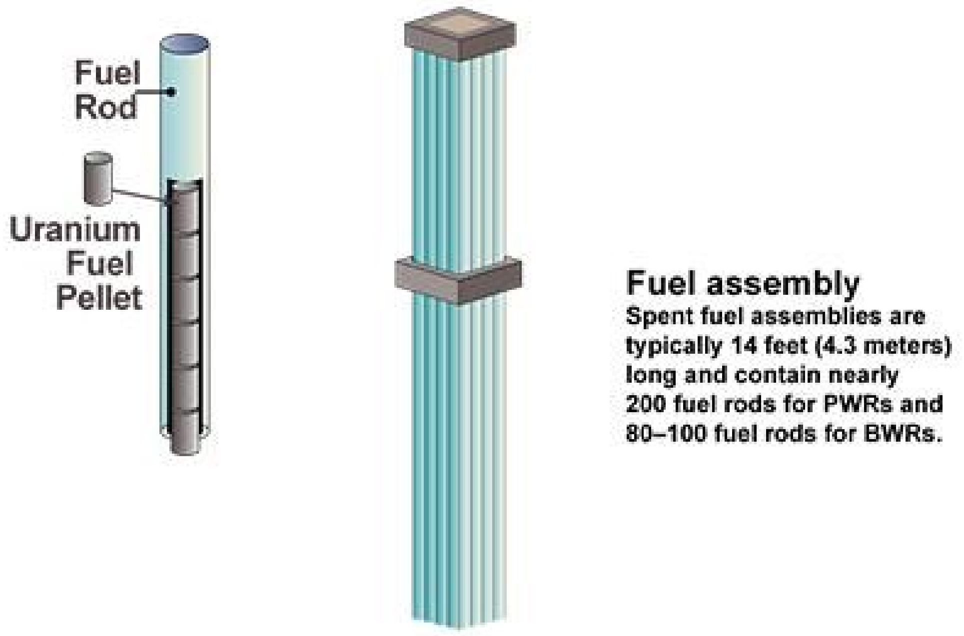
reactor coolant - a substance circulated through a nuclear reactor to remove or transfer heat (most commonly – water); other possible coolants - heavy water, air, carbon dioxide, helium, liquid sodium, or sodium-potassium alloy.

control rods – rods or tubes containing a neutron absorbing material such as boron, hafnium, cadmium used to control the power of a nuclear reactor; a control rod is removed from or inserted into the reactor core to increase or decrease the reactor's reactivity (increase or decrease the neutron flux); this, in turn, affects the reactor's thermal power, the amount of steam produced, and hence the electricity generated.



shield/containment system is fitted around the reactor to absorb any radiation from leaking into its immediate environment; usually made of lead or special types of plastics, shielding is necessary for both the transportation and storage of radioactive neutron sources.





Radiation exposures from nuclear fuel cycle

Nuclear fuel cycle consists of

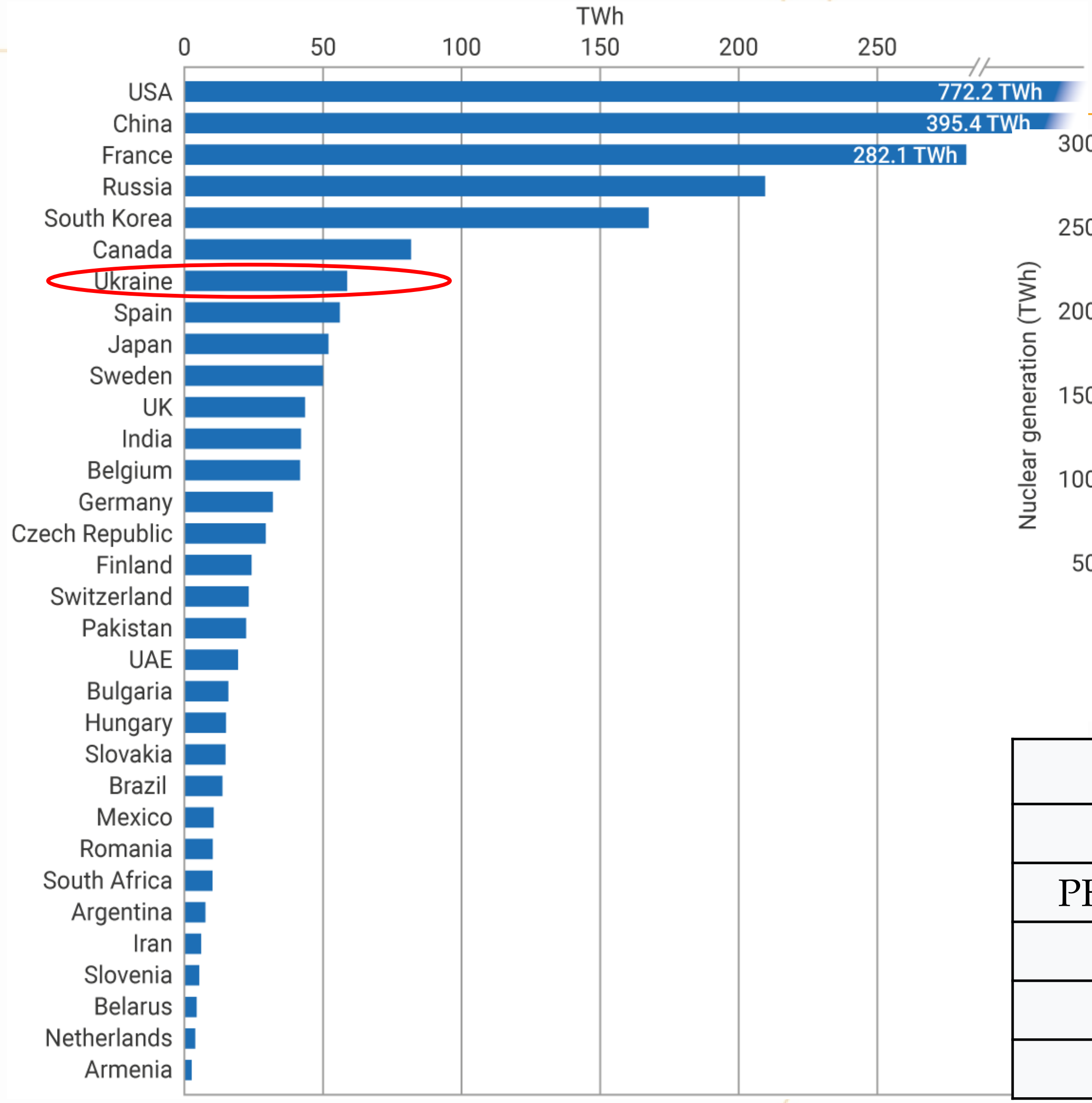
steps in the front end (*the preparation of the fuel*),
steps in the service period (*fuel burnup*),
steps in the back end (*reprocessing or disposal of spent nuclear fuel*).

Radiation exposures from the nuclear fuel cycle are evaluated from the entire life cycle of nuclear fuel, and this includes:

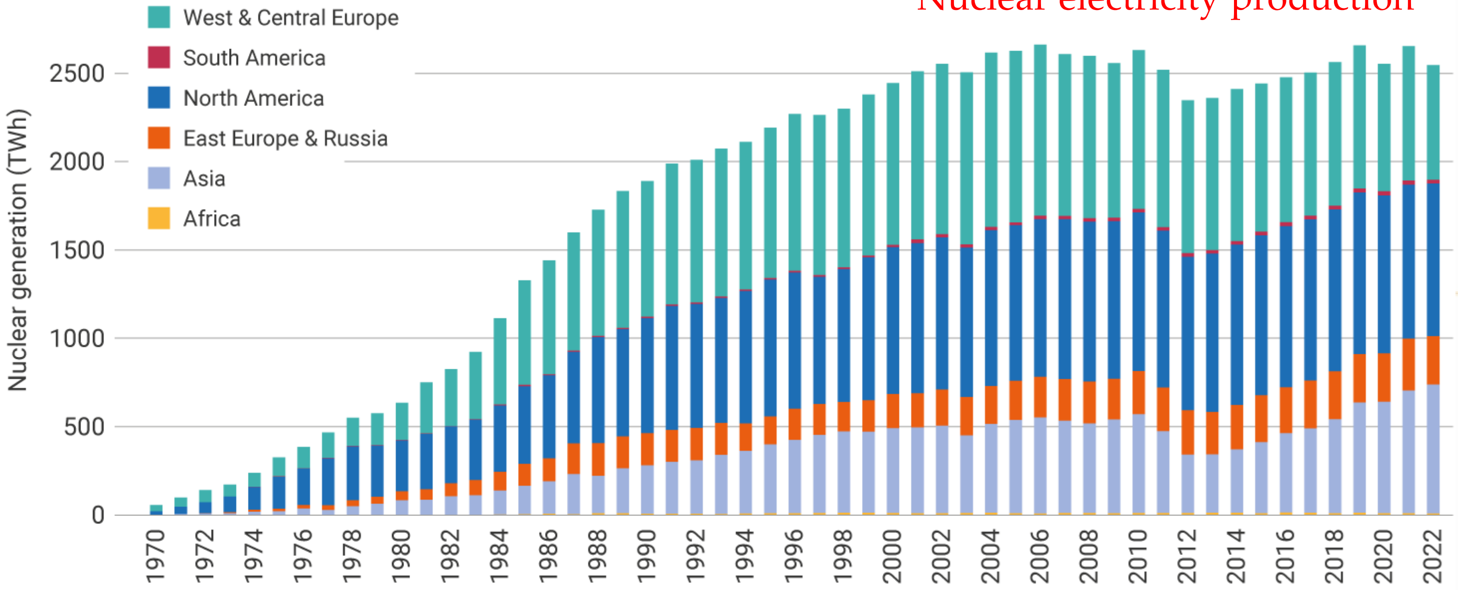
uranium mining, milling and mill tailings,
fabrication of fuel assemblies
power plant operation (except accidents),
spent fuel storage or reprocessing,
disposal of radioactive waste,
decommissioning activities.

The collective dose, which results from the nuclear fuel cycle, is: 130 man Sv for nuclear fuel cycle (half of the contribution to public exposure from the nuclear fuel cycle comes from discharges of radionuclides during uranium mining).

Nuclear power in the world today



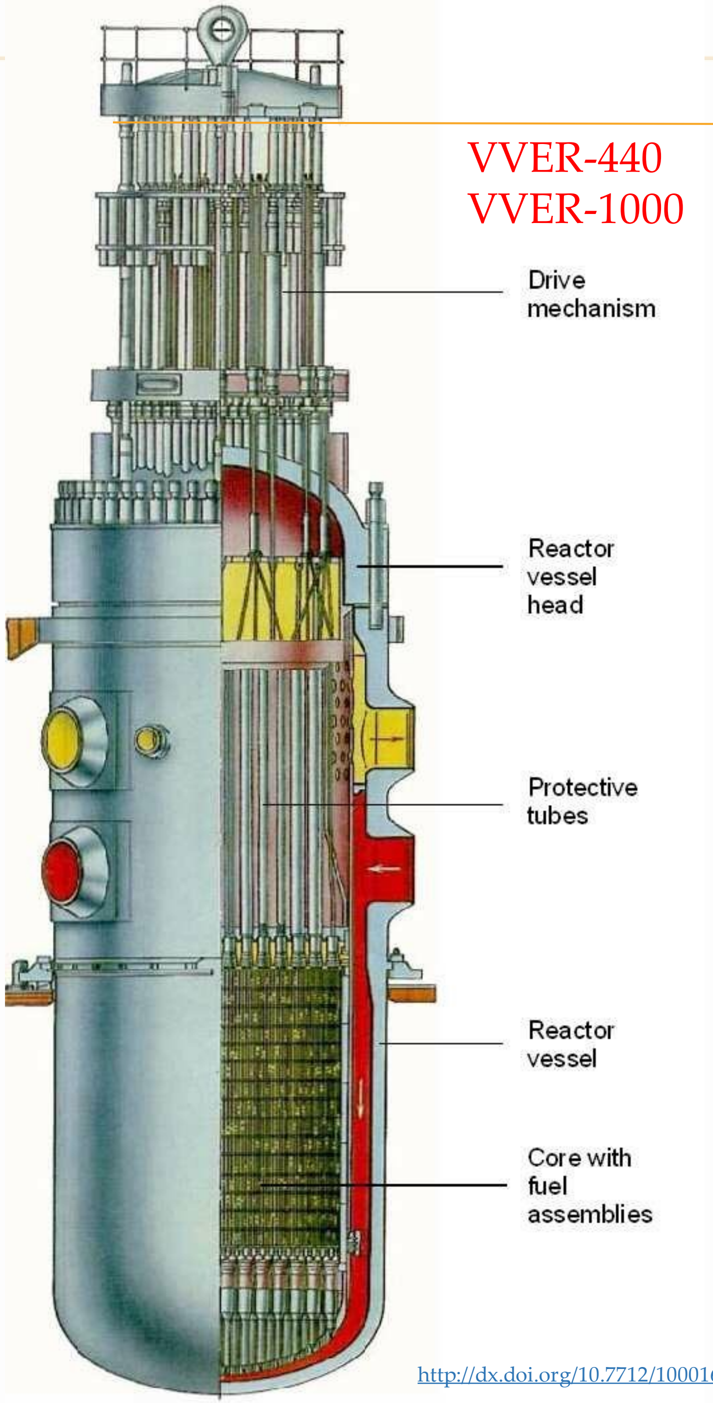
Nuclear electricity production



PWR (pressurized water reactor)	297
BWR Boiling Light-Water Cooled and Moderated Reactor	75
PHWR (Pressurized Heavy-Water Moderated and Cooled Reactor)	49
LWGR (Light-Water Cooled, Graphite Moderated Reactor)	15
GCR (Gas Cooled, Graphite Moderated Reactor)	14
FBR (Fast Breeder Reactor)	3

Nuclear energy now provides about 10% of the world's electricity from about 450 reactors.
Nuclear energy provides about one-quarter of the world's low-carbon electricity.
Nuclear energy is the world's second largest source of low-carbon power (26% of the total in 2020).
Over 50 countries utilize nuclear energy in about 220 research reactors.

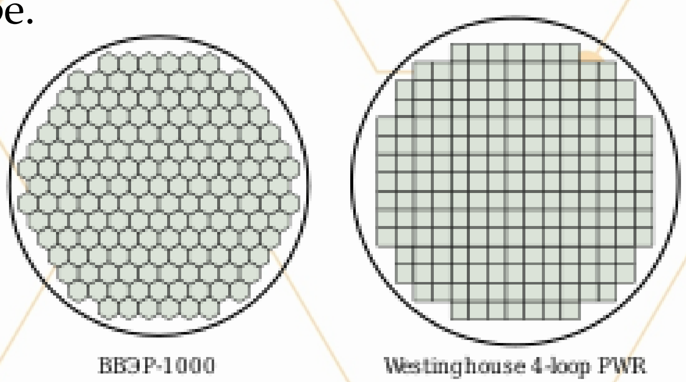
Nuclear power in Ukraine



VVER-440
VVER-1000

A WWER-1000 (or VVER-1000 as a direct transliteration of Russian ВВЭР-1000), a 1000 MWe Russian nuclear power reactor of PWR type.

Control rod drives
Reactor vessel head
Reactor pressure vessel
Inlet and outlet nozzles
Reactor core
Fuel rods

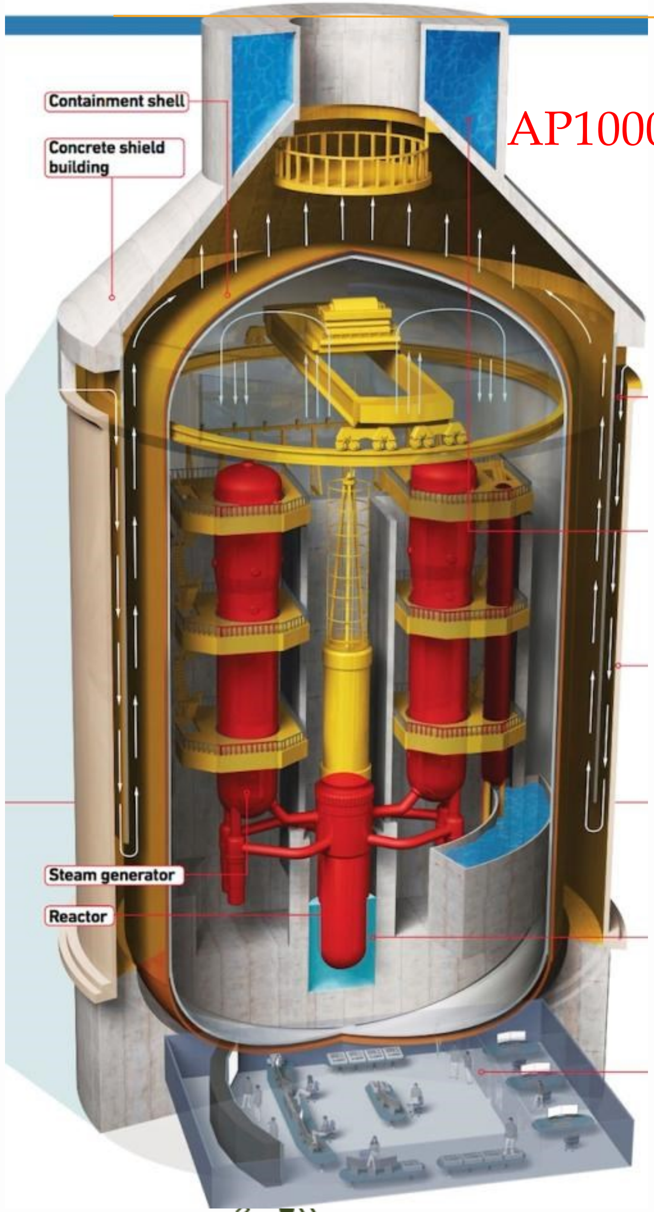


Developer - Kurchatov Institute, Russia - Water-cooled water-moderated energy reactor

Reactor fuel rods are fully immersed in water at about 15 MPa pressure so that it does not boil at the normal operating temperatures (220 to over 320°C).
Water in the reactor serves both as a coolant and a moderator - important for safety. Should coolant circulation fail, the neutron moderation effect of the water diminishes due to increased heat, which creates steam bubbles which do not moderate neutrons, thus reducing reaction intensity and compensating for loss of cooling, a condition known as negative void coefficient.
Fuel is low enriched (2.4–4.4% ^{235}U) uranium dioxide (UO_2) or equivalent pressed into pellets and assembled into fuel rods.
Reactivity is controlled by control rods that can be inserted into the reactor from above. These rods are made from a neutron absorbing material and, depending on depth of insertion, hinder the chain reaction. If there is an emergency, a reactor shutdown can be performed by full insertion of the control rods into the core.

http://dx.doi.org/10.7712/100016.2447.9407

Developer - Westinghouse Electric Company, USA- Water-cooled water-moderated energy reactor

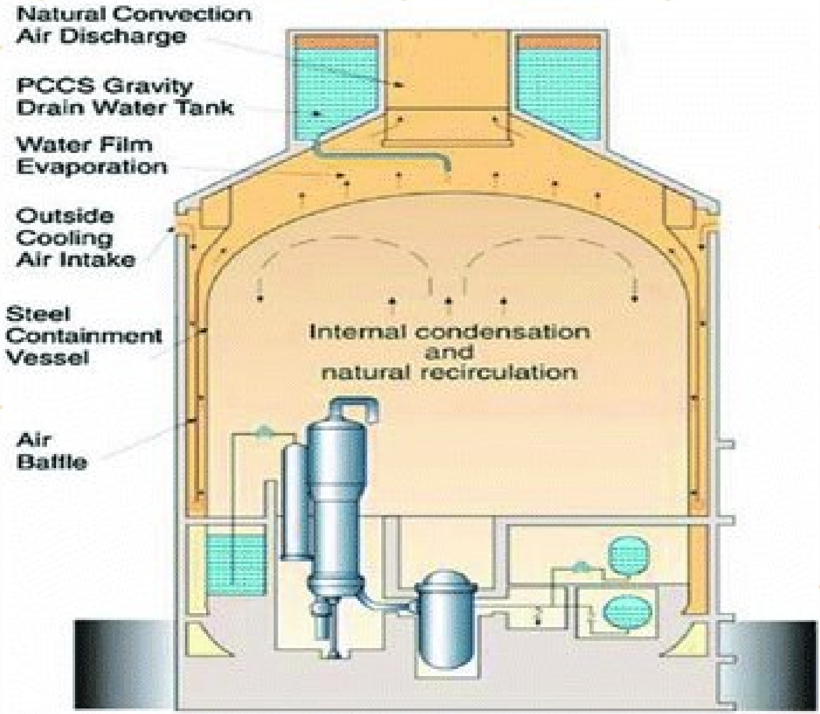


AP1000

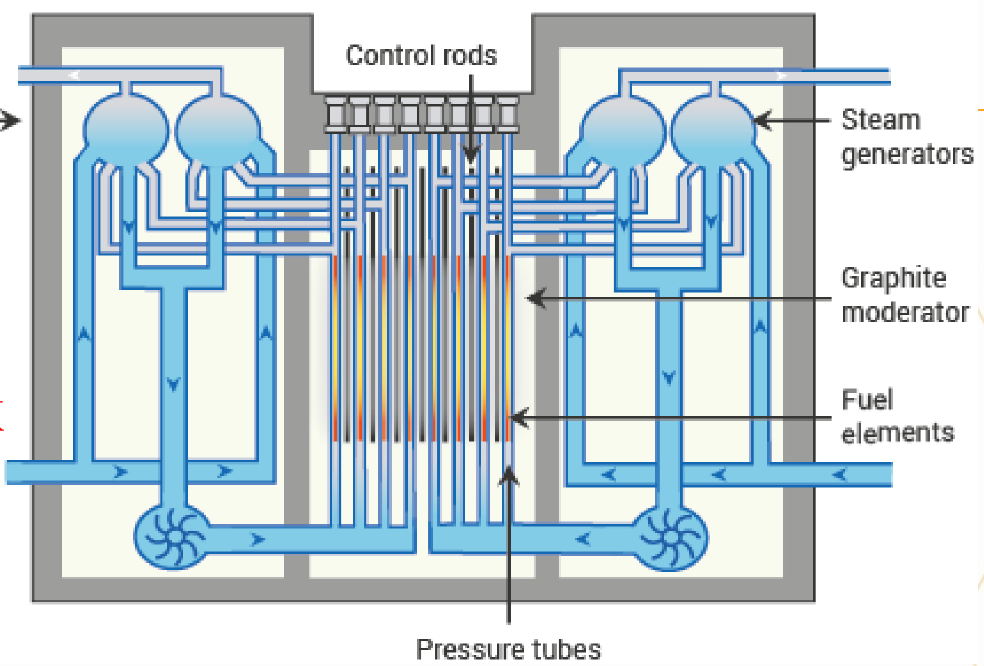
The AP1000 is a pressurized water reactor (PWR) with two cooling loops.

The AP1000 design is considerably more compact in land usage than most existing PWRs and uses under a fifth of the concrete and rebar reinforcing of older designs.
Probabilistic risk assessment was used in the design of the plants – maximum core damage frequency of 5.09×10^{-7} per plant per year.
Used fuel produced by the AP1000 can be stored indefinitely in water on the plant site.
Aged used fuel may also be stored in above-ground dry cask storage

Power reactors of all types continue to produce heat from radioactive decay products even after the main reaction is shut down, so it is necessary to remove this heat to avoid meltdown of the reactor core. AP1000 uses a tank of water situated above the reactor. When the passive cooling system is activated, the water flows by gravity to the top of the reactor where it evaporates to remove heat. The system uses multiple valves which must operate within the first 30 minutes. This is designed to happen even if the reactor operators take no action. The electrical system required for initiating the passive systems doesn't rely on external or diesel power and the valves don't rely on hydraulic or compressed air systems.



https://www.iaea.org/sites/default/files/21/07/iaea_webinar_marine-based_smrs_ofnp_m_golay_18may2021.pdf



RBMK

RBMK is a water-cooled reactor with individual fuel channels and using graphite as moderator (light water graphite reactor or LWGR). As a boiling water reactor (BWR), water boils in the fuel channels (at about 6.9 MPa) and steam is separated above them in a single circuit (designed over 1964-66 and is very different from today reactors).

The void coefficient is a number that can be used to estimate how much the reactivity of a nuclear reactor changes as voids (typically steam bubbles) form in the reactor moderator or coolant.

Positive void coefficient

Reactors cooled by boiling water will contain a steam in the core. Because water is both a more efficient coolant and a more effective neutron absorber than steam, a change in the proportion of steam bubbles, or 'voids', in the coolant will result in a change in core reactivity.

When the void coefficient is negative, an increase in steam will lead to a decrease in reactivity. In reactors where the same water acts as both moderator and coolant, excess steam generation reduces the slowing of neutrons necessary to sustain the nuclear chain reaction.

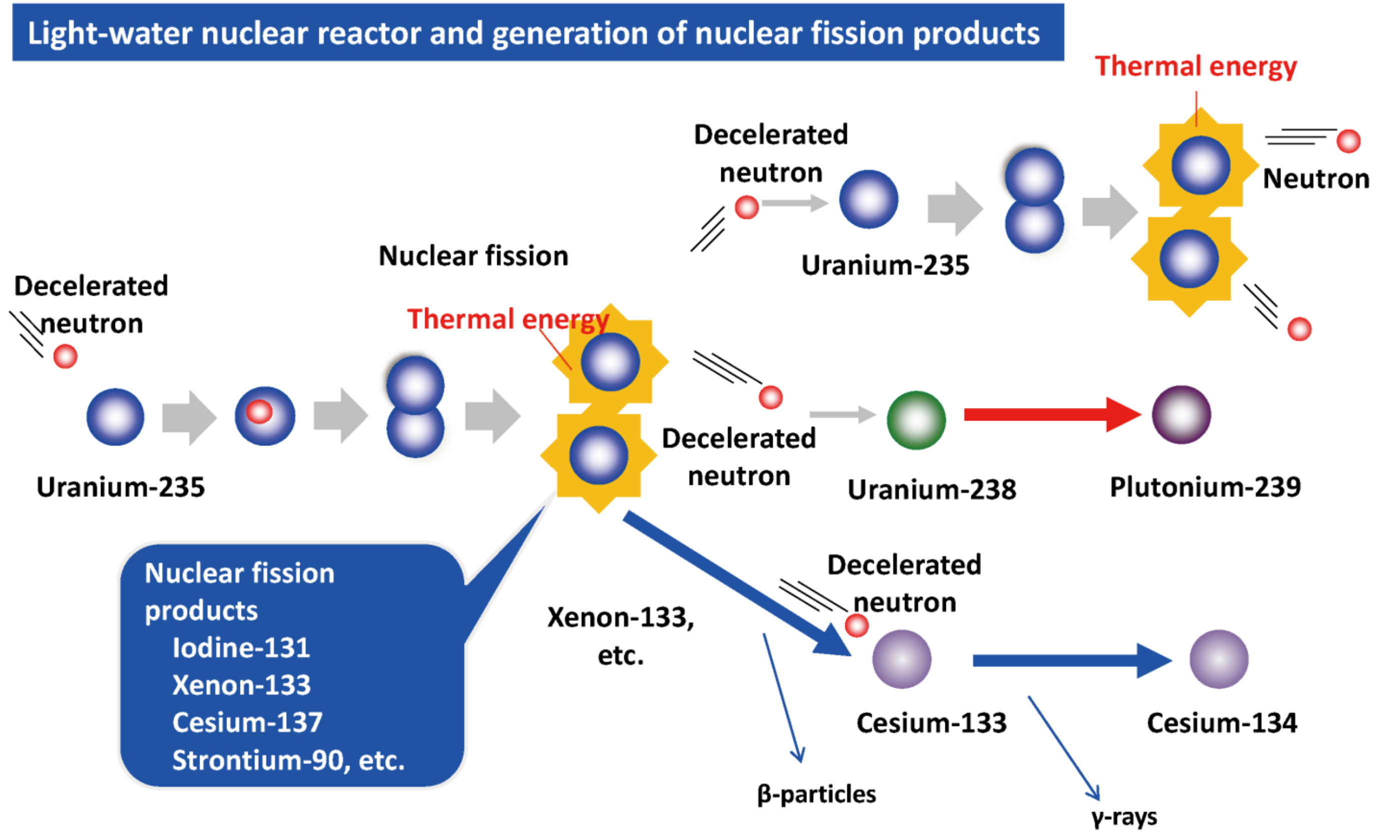
In reactor designs where the moderator and coolant are of different materials, excess steam reduces the cooling of the reactor, but as the moderator remains intact the nuclear chain reaction continues.

In RBMK, the neutron absorbing properties of the cooling water are a significant factor in the operating characteristics. In such cases, the reduction in neutron absorption as a result of steam production, and the consequent presence of extra free neutrons, enhance the chain reaction. ***This leads to an increase in the reactivity of the system.***

The void coefficient is only one contributor to the overall power coefficient of reactivity, but in RBMK reactors, it is the dominant component, reflecting a high degree of dependence of reactivity on the steam content of the core.

Nuclear Disaster

Products in Nuclear Reactors



The light-water nuclear reactor is currently the most widely used type of reactor around the world.

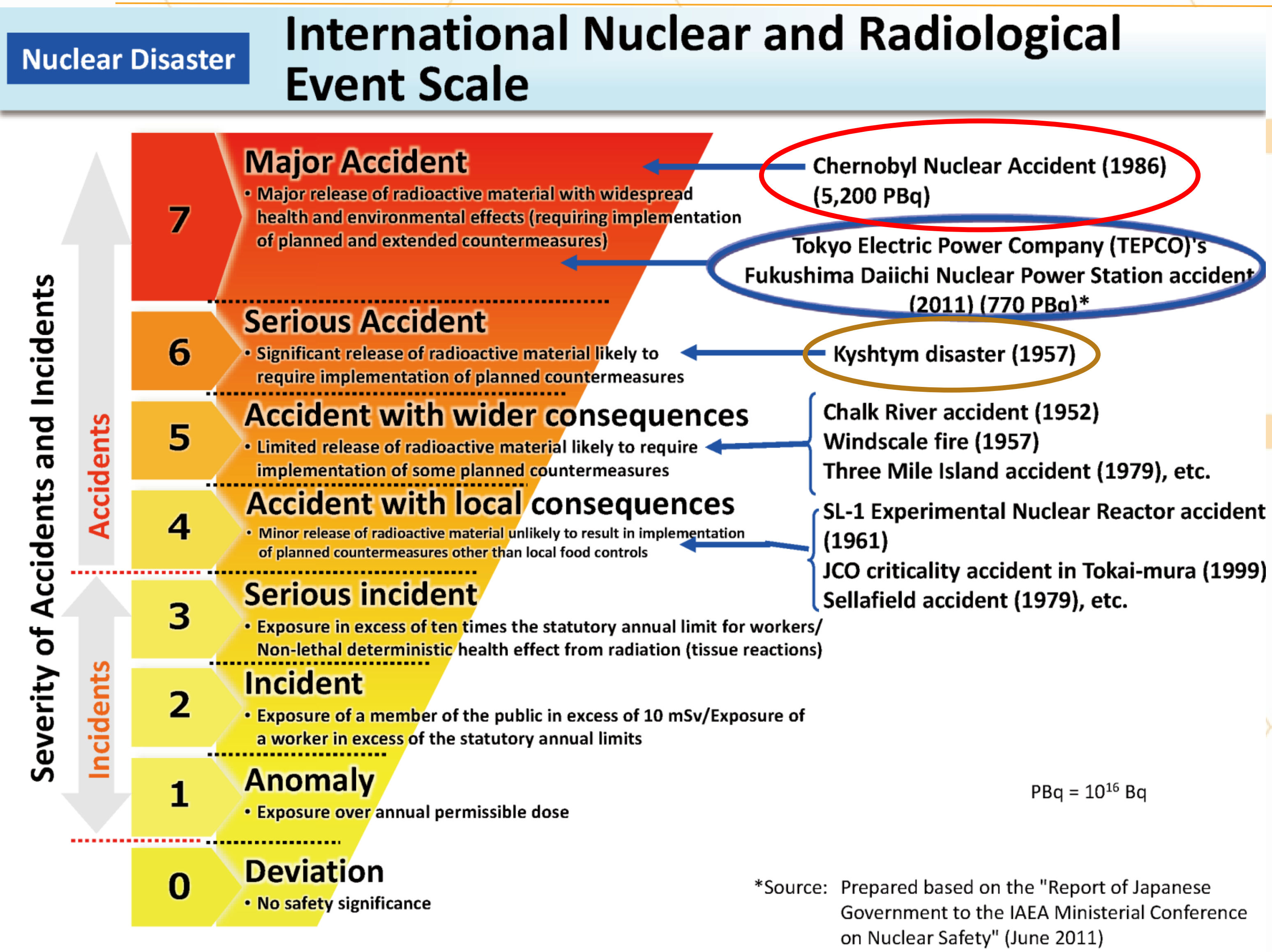
Bombarding enriched uranium fuel (*Uranium-235: 3-5%; Uranium-238: 95-97%)* with neutrons results in nuclear fission. Radioactive nuclear fission products such as *Iodine-131, Cesium-137, and Strontium-90* are created in this process.

When Uranium-238 is bombarded with neutrons, *Plutonium-239* is created.

Cesium-134 is not created directly from the nuclear fission of Uranium-235. Through beta disintegration, Xenon-133 and the like, which are nuclear fission products, disintegrate into Cesium-133, and Cesium-133 then turns into Cesium-134 as decelerated neutrons are trapped. As long as the reactor is working properly, these products remain in nuclear fuel rods and do not leak out of the reactor.

Nuclear facilities are equipped with a variety of mechanisms for preventing leakage of radioactive materials, but if they all stop functioning properly, radioactive leaks will occur.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-02-03.html

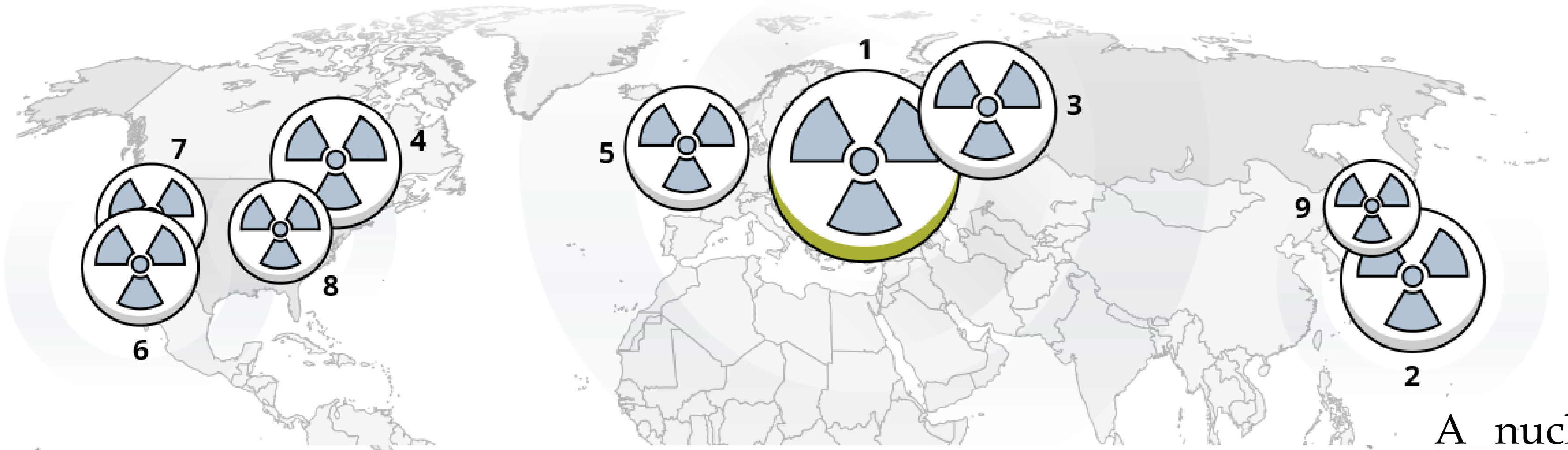


The International Nuclear and Radiological Event Scale (INES) was established by the INES (the International Atomic Energy Agency) and the OECD/NEA (Organization for Economic Co-operation and Development/Nuclear Energy Agency), and in 1992, all countries were recommended to formally adopt it.

Incidents and accidents at nuclear facilities are divided into seven categories according to their severity. Each country determines the severity of incidents or accidents using this scale and announces the results.

The *Chornobyl* and TEPCO's *Fukushima* Daiichi *accidents* were provisionally rated Level 7, indicating that they were the most serious accidents because of the amount of radioactive material released.

Nuclear accidents



1 Chernobyl disaster	**2** Fukushima accident	**3** Kyshtym disaster	**4** Accident at Chalk River
◼ 7	◼ 7	◼ 6	◼ 5
Where: Ukraine, USSR When: April 26, 1986	Where: Japan When: March 11, 2011	Where: Russia, USSR When: September 29, 1957	Where: Canada When: December 12, 1952

5 Windscale fire	**6** Leakage of radioactive gases at Santa Susana Field Laboratory	**7** Release of radioactive iodine at the SL-1	**8** Three Mile Island accident	**9** Radiation accident in the Chazhma Bay
◼ 5	◼ 5	◼ 5	◼ 5	◼ 5
Where: UK When: October 10, 1957	Where: USA When: July 26, 1959	Where: USA When: January 3, 1961	Where: USA When: March 28, 1979	Where: Sea of Japan, USSR When: August 10, 1985

A nuclear and radiation accident is defined by the International Atomic Energy Agency (IAEA) as "*an event that has led to significant consequences to people, the environment or the facility. Examples include lethal effects to individuals, large radioactivity release to the environment, reactor core melt*"

Nuclear Disaster

Radioactive Materials Derived from Nuclear Accidents

	H-3 Tritium	Sr-90 Strontium-90	I-131 Iodine-131	Cs-134 Cesium-134	Cs-137 Cesium-137	Pu-239 Plutonium-239
Types of radiation	β	β	β, γ	β, γ	β, γ	α, γ
Biological half-life	10 days *1 *2	50 years *3	80 days *2	70-100 days *4	70-100 days *3	Liver: 20 years *5
Physical half-life	12.3 years	29 years	8 days	2.1 years	30 years	24,000 years
Effective half-life (calculated from biological half-life and physical half-life)	10 days	18 years	7 days	64-88 days	70-99 days	20 years
Organs and tissues where radioactive materials accumulate	Whole body	Bones	Thyroid	Whole body	Whole body	Liver and bones

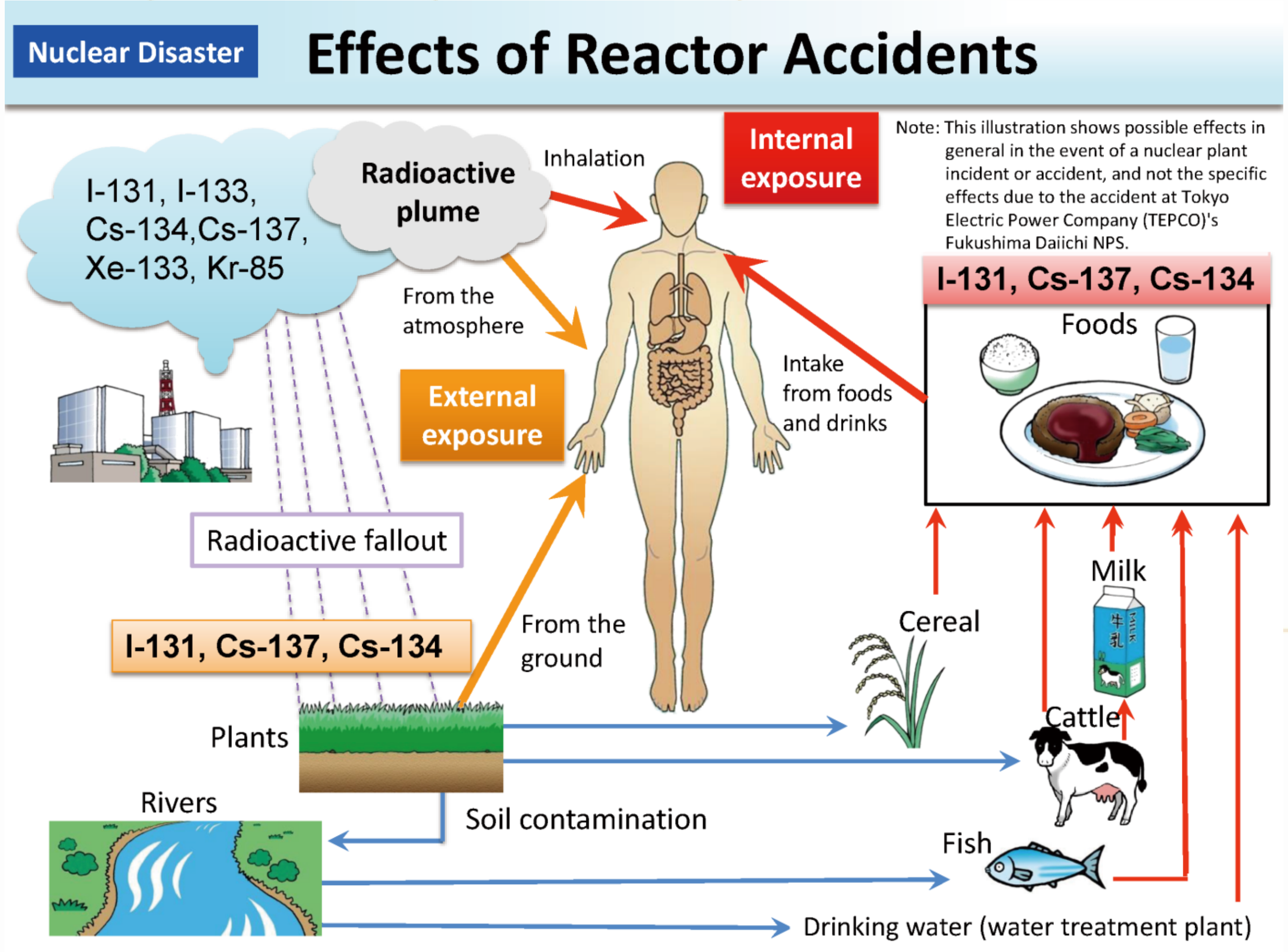
Four types of radioactive materials, Iodine-131, Cesium-134, Cesium-137, and Strontium-90, are the major concerns in relation to health and environment.

Iodine-131 has a short physical half-life of about 8 days, but once it enters the body, 10-30% will accumulate in the thyroid. If this happens, the thyroid will continue to be locally exposed to β-particles and γ-rays for a while.

Cesium-134 and Cesium-137 are the major causes of contamination due to nuclear plant accidents. Cesium-137 has a long physical half-life of 30 years and continues to contaminate the environment for a long time. Since radioactive cesium has similar chemical properties to potassium, it will be distributed throughout the body, like potassium. The biological half-lives of cesium and iodine vary depending on the age of the person, and are known to become shorter, the younger the person is.

Strontium-90 has a long physical half-life, and once it enters the body, it accumulates in bones because of its chemical properties similar to calcium. Since it does not emit γ-rays, it is not as easy as in the case of Cesium-134 and Cesium-137 to detect where and how much it exists in the body. In a nuclear plant accident, Strontium-90 is also produced as a result of nuclear fission, though smaller in quantity than Cesium-134 and Cesium-137.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-02-04.html



If an emergency happens in a nuclear facility and radioactive gas leaks, it flows into the atmosphere in a state called "plume“. Plumes contain *radioactive noble gases and aerosols* (micro-liquid droplets and particles), such as *radioactive iodine* and *radioactive cesium*.

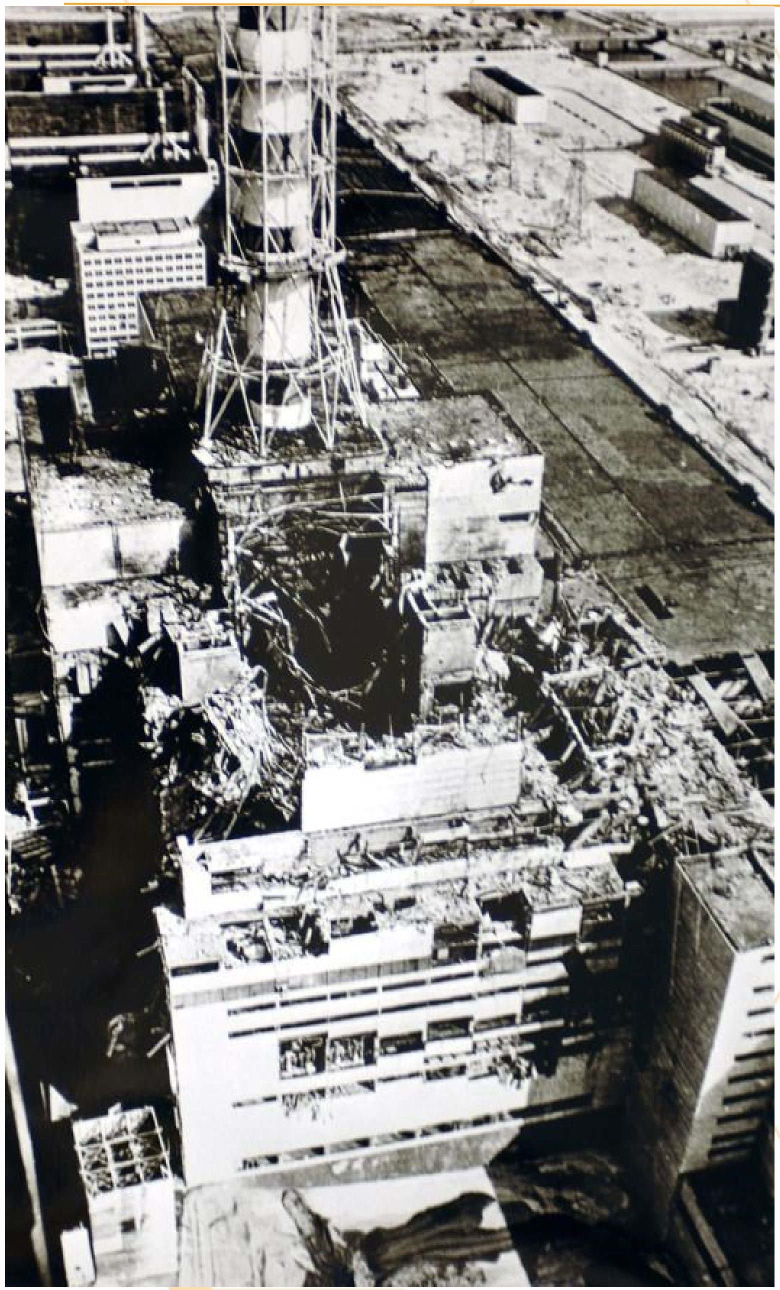
When a plume passes overhead, people under it are externally exposed to radiation from radioactive materials contained therein. Additionally, people who inhale radioactive materials contained in the plume are also internally exposed to radiation.

Radioactive noble gases are not deposited on the ground, and even if they enter the human body through inhalation, they *do not remain in the body*.

Aerosols, such as radioactive iodine and radioactive cesium, fall down gradually while a plume passes through and is deposited on the ground surface and plants.

External exposure from deposited radioactive materials may occur even after the plume has passed, and internal exposure may also occur if someone consumes contaminated drinking water or foods.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-02-02.html



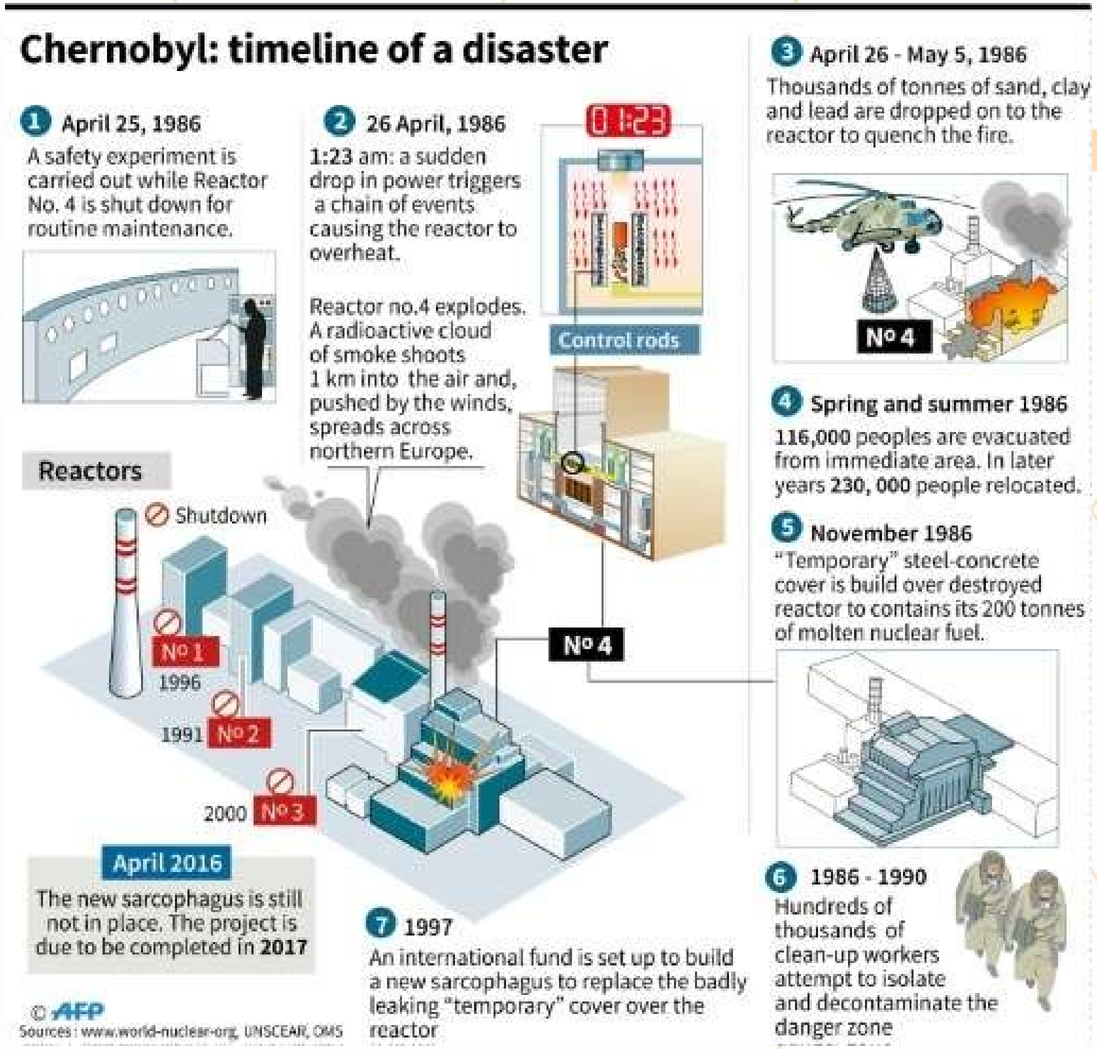
At the time of the accident at Chornobyl, the void coefficient of reactivity was so positive that it overwhelmed the other components of the power coefficient, and the power coefficient itself became positive.

When the power began to increase, more steam was produced, which in turn led to an increase in power. The additional heat resulting from the increase in power raised the temperature in the cooling circuit and more steam was produced.

More steam means less cooling and less neutron absorption, resulting in a rapid increase in power to 100 times the reactor's capacity.

The true death toll of the Chornobyl disaster is difficult to judge because of the long-lasting health effects of radioactive pollution.

The official death toll directly attributed to Chornobyl, which is recognized by the international community, is just 31 people.



April 25, 1986, 1 a.m.

Chornobyl's operators begin reducing power at reactor No. 4 for a safety test, which they have timed to coincide with a routine shutdown for maintenance. The test is supposed to determine whether, in the event of a power failure, the plant's still-spinning turbines can produce enough electricity to keep coolant pumps running during the brief gap before the emergency generators kick in.

April 25, 1986, 2 p.m.

Reactor No.4's emergency core cooling system is disabled to keep it from interfering with the test.

April 25, 1986, 11:10 p.m.

Operators receive permission for a test and shutdown. The less-experienced night shift never received proper instructions on how to perform the test.

April 26, 1986, 12:28 a.m.

Power plummets to far below the level at which the reactor is considered stable. Operators respond by removing most of the control rods in violation of the plant's safety guidelines, yet they still have trouble raising the power.

April 26, 1986, 1 a.m.

The power stabilizes, albeit at a lower than preferred level, and plant supervisors order the test to proceed. The automatic emergency shutdown is turned off.

April 26, 1986, 1:23:04 a.m.

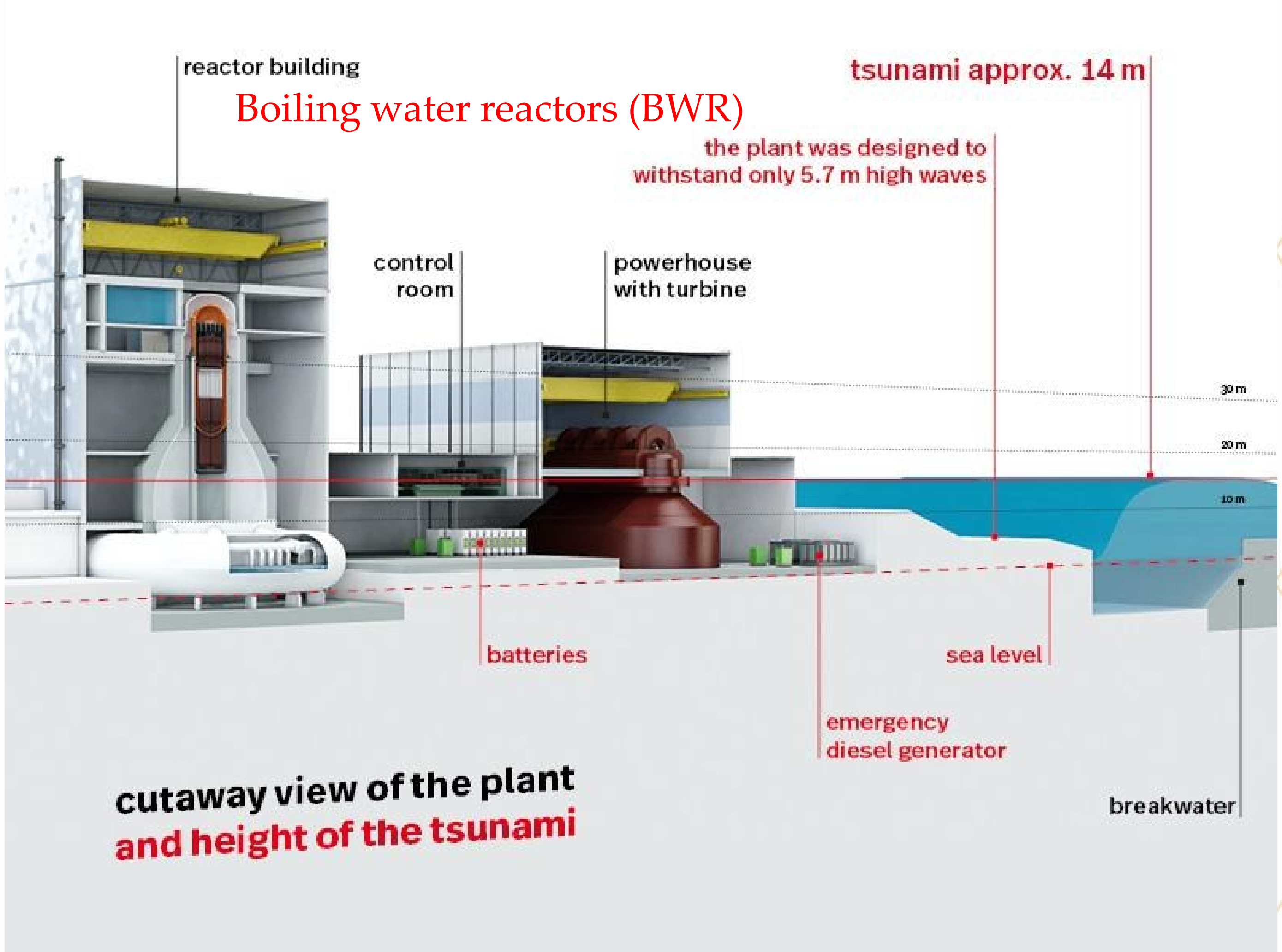
The test officially begins, and an unexpected power surge occurs.

April 26, 1986, 1:23:40 a.m.

An operator presses the emergency shutdown button, but the control rods jam as they enter the core.

April 26, 1986, 1:23:58 a.m.

The first explosion, to be quickly followed by at least one more, blows the 1,000-ton roof right off the reactor and shoots a fireball into the night sky.



The Fukushima nuclear accident was a major nuclear accident at the Fukushima Daiichi nuclear power plant in, Japan on March 11, 2011.

The cause of the accident was the 2011 Tohoku earthquake and tsunami, which resulted in electrical grid failure and damaged nearly all of the power plant's backup energy sources. The subsequent inability to sufficiently cool reactors after shutdown compromised containment and resulted in the release of radioactive contaminants into the surrounding environment.

No adverse health effects among Fukushima residents or power station workers have been documented that are directly attributable to radiation exposure from the accident. Following the accident, at least 164,000 residents of the surrounding area were permanently or temporarily displaced. This response resulted in at least 51 fatalities (with more attributed to subsequent stress or fear of radiological hazards).

https://www.base.bund.de/EN/ns/accidents/fukushima/fukushima.html

March 11, 2011

At 2:46 PM, a 9.0 magnitude earthquake strikes off Honshu island. Reactors 1, 2, and 3 at the Fukushima plant automatically shut down, reactors 4, 5, and 6 were already offline for maintenance at the time. The plant was initially being cooled by backup generators.
An hour later, a 14 m tsunami hits, overflowing the 6 m seawall, inundating the plant, and disabling all generators. Most of the emergency core cooling system fails.

March 12, 2011

The emergency backup battery for reactor 3 runs out and the fuel rods are exposed.
Some steam is released into the air. As the situation in the 3 reactors worsens, the evacuation zone is extended – first to 10 km then to 20 km.

March 13, 2011

Core damage begins in unit 3, unit 2 is thought to be stable.

March 14, 2011

A major explosion in the building for reactor 3 damages the cooling system for reactor 2, triggering core damage in that unit.

March 15, 2011

An explosion severely damages reactor 4. Another explosion takes place in unit 3. A fire starts in unit 4. Radiation near reactor 3 is measured at 0.4 Sv/h

March 17, 2011

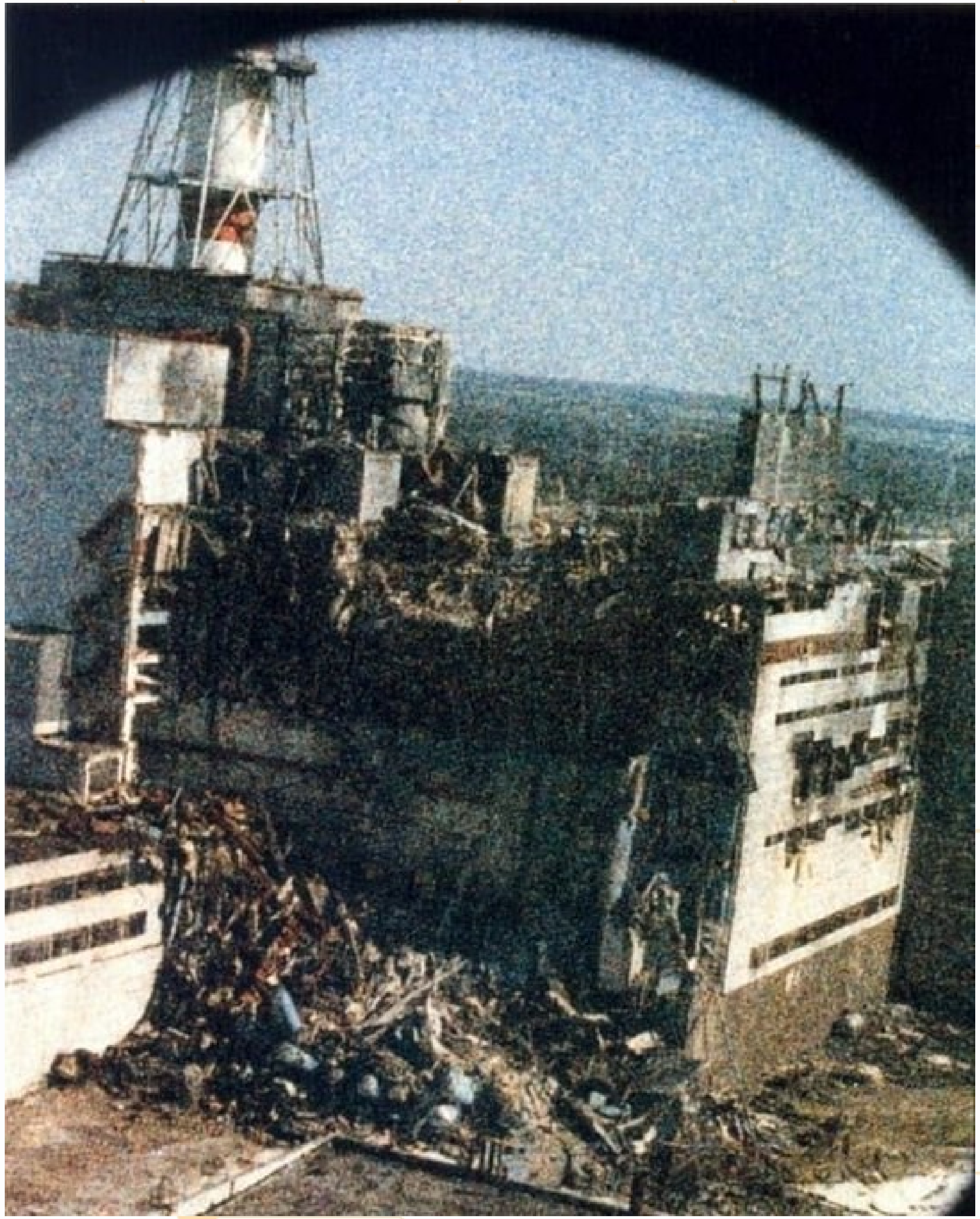
Construction begins to hook up an external power source to all 6 units. Helicopters are brought in to drop water on spent fuel pools in units 3 and 4.

March 18, 2011

30 fire engines from Tokyo Fire Company begin spraying water on the afflicted reactors.

March 20, 2011

Power is successfully connected to unit 2. A generator providing power for units 5 and 6 is repaired, allowing them both to be brought to a cold shutdown state.



This is the first image captured of Chornobyl, taken 14 hours after the explosion on April 26, 1986.

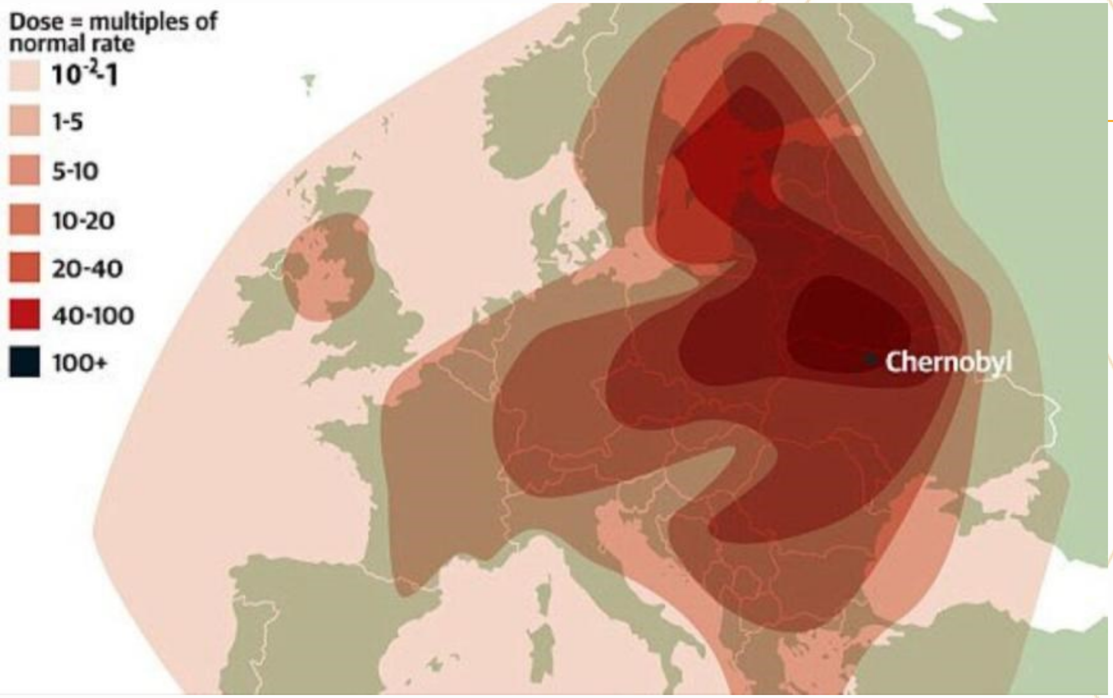
The photo was snapped from a helicopter assessing radiation levels over the disaster area. The image is grainy due to the intense radiation in the air, which began damaging the camera film as soon as it was exposed.

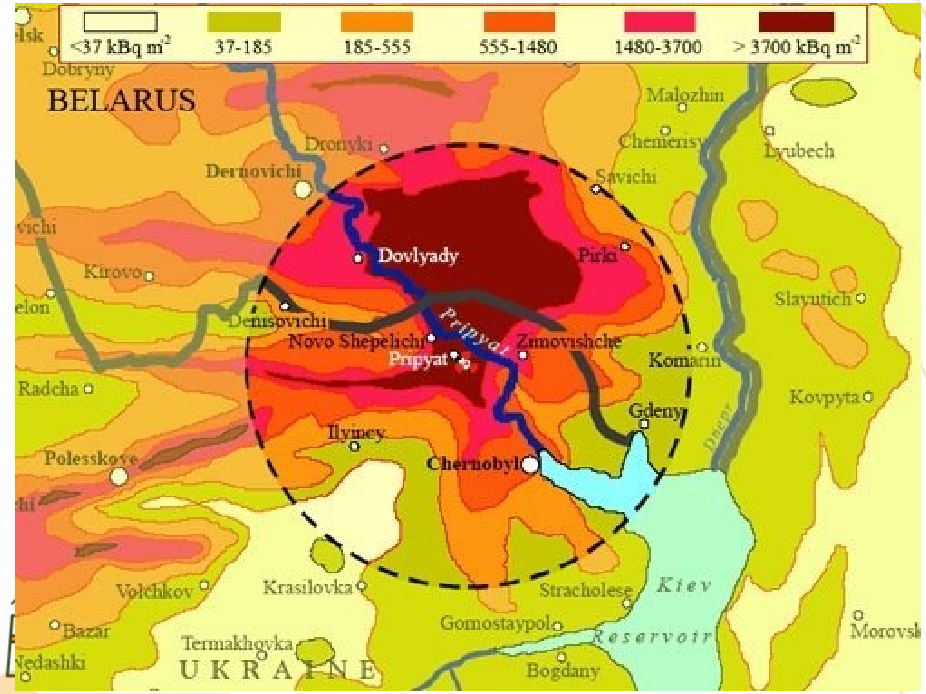
Igor Kostin, the photographer, found that the radiation affected his camera's motors after about 20 photos. When he processed his films, only the image above was usable. All other photos, affected by high radiation levels, came out completely black.

His images helped reveal the catastrophe to the world.

Despite his closeness to the site, Kostin did not receive deadly amounts of radiation.

He died in a car crash in 2015 when he was 78.



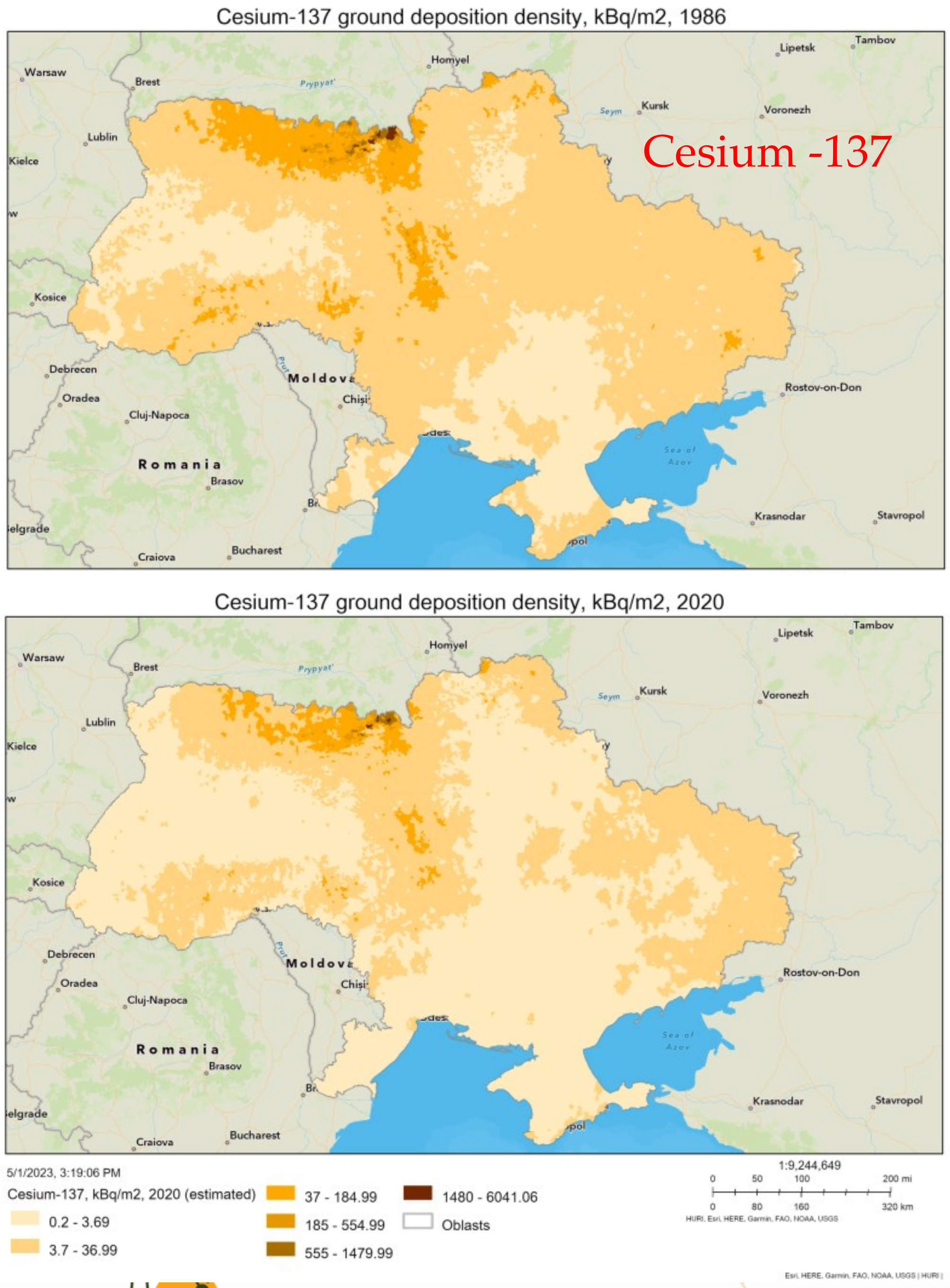


Average effective doses to individuals most affected by the accident was about 120 mSv for 530,000 recovery operation workers, 30 mSv for 115,000 evacuated people and 9 mSv during the first two decades after the accident to those who continued to reside in contaminated areas.

BUT the typical dose from a single computed tomography scan is 9 mSv.

The radionuclides released from the reactor that caused exposure of individuals were mainly iodine-131, caesium-134 and caesium-137.

Iodine-131 has a short radioactive half-life (eight days), but it can be transferred to humans relatively rapidly from the air and through consumption of contaminated milk and leafy vegetables. Iodine becomes localized in the thyroid gland.



Chornobyl caused radiation pollution. Cesium-137

Half-life: 30.17 years

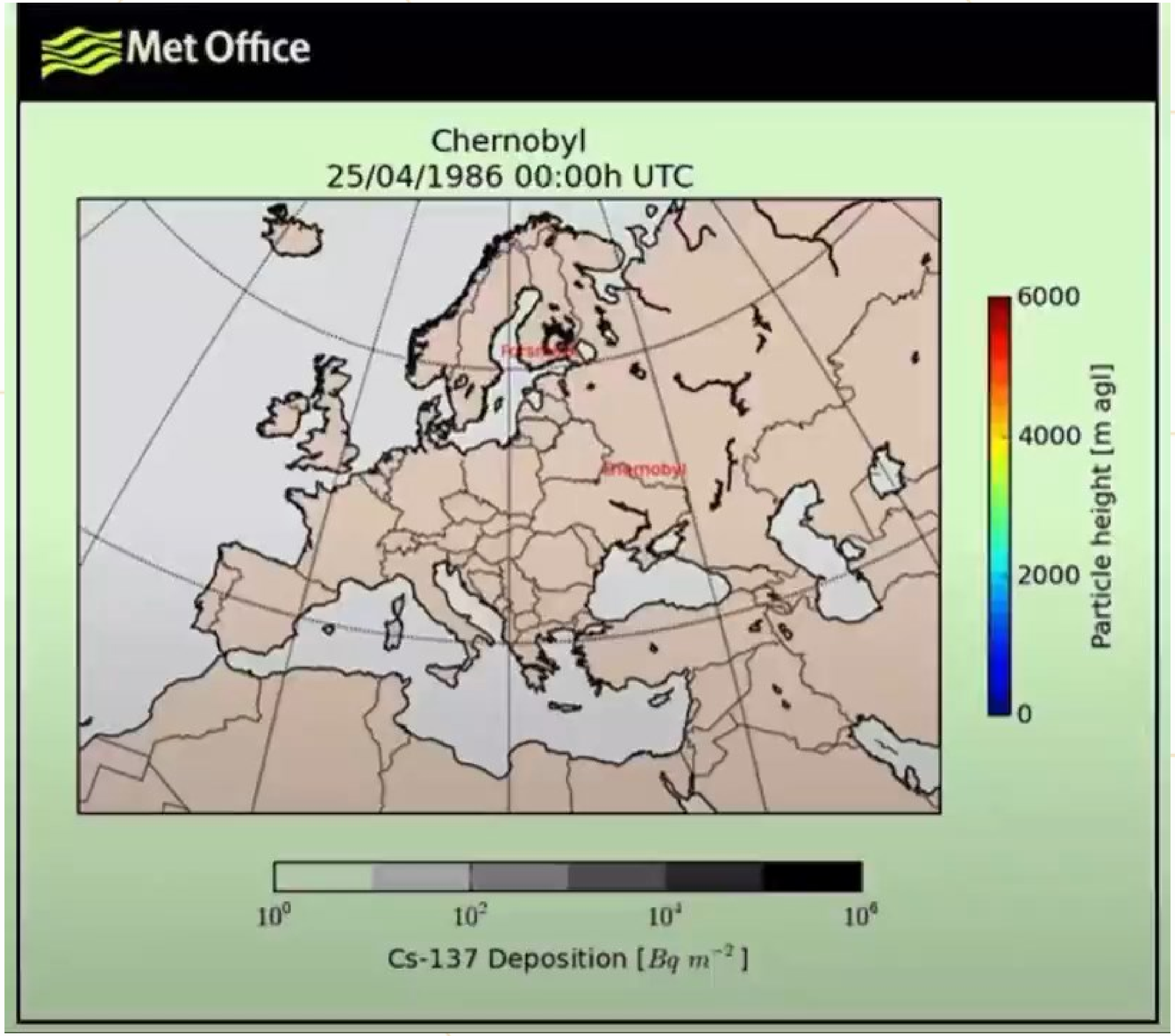
Mode of decay: Beta and gamma radiation

Cs-137 is one of the byproducts of nuclear fission processes in nuclear reactors and nuclear weapons testing.

Small quantities of Cs-137 can be found in the environment from nuclear weapons tests that occurred in the 1950s and 1960s and from nuclear reactor accidents, such as the Chornobyl power plant accident in 1986, which distributed Cs-137 to many countries in Europe.

Exposure to Cs-137 can increase the risk for cancer because of the presence of high-energy gamma radiation. Internal exposure to Cs-137 through ingestion or inhalation allows the radioactive material to be distributed in the soft tissues, especially muscle tissue, which increases cancer risk.

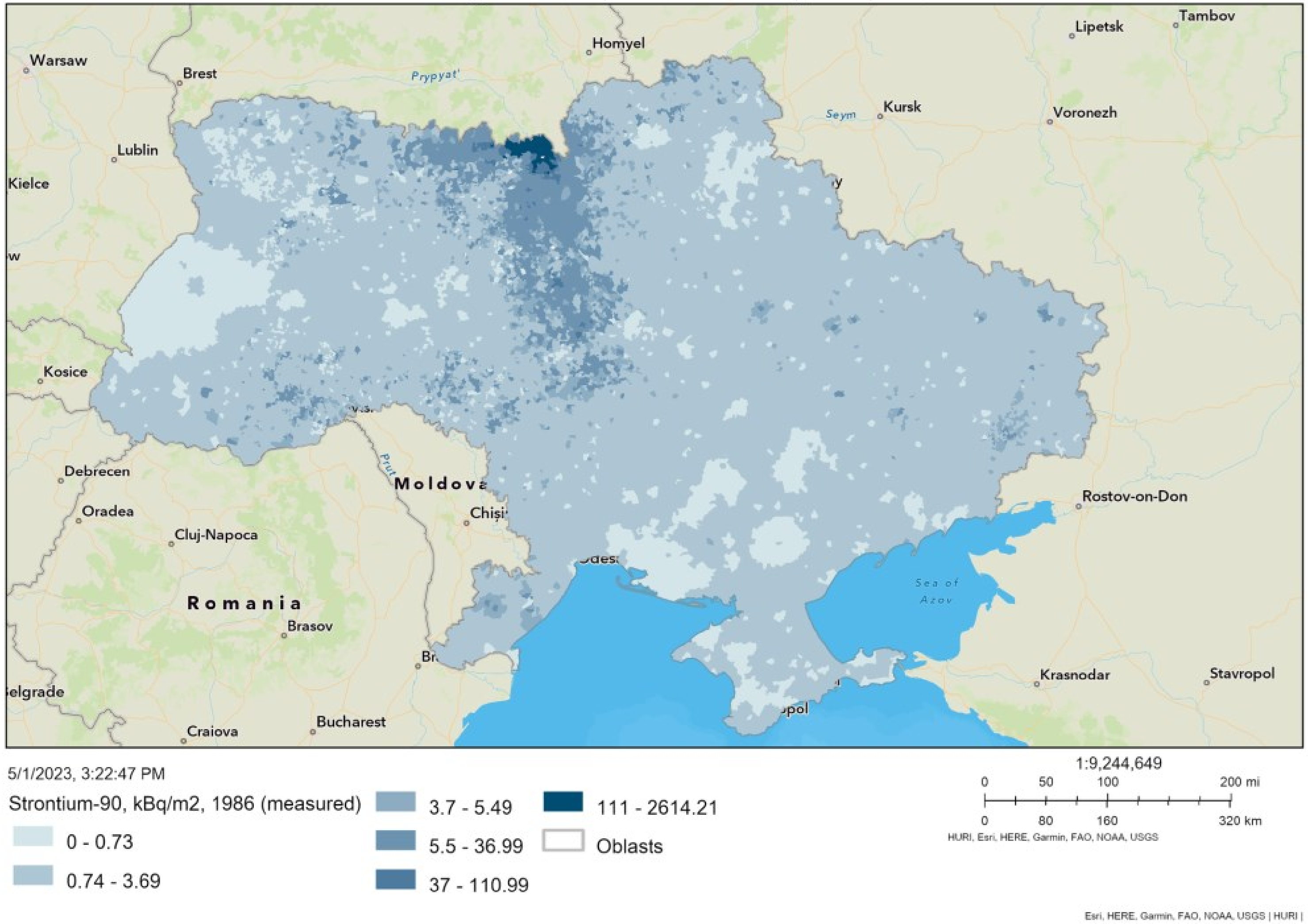
https://huri.harvard.edu/news/mapa-advances-research-chornobyl-Chornobyl-nuclear-disaster



Chernobyl radiation spread

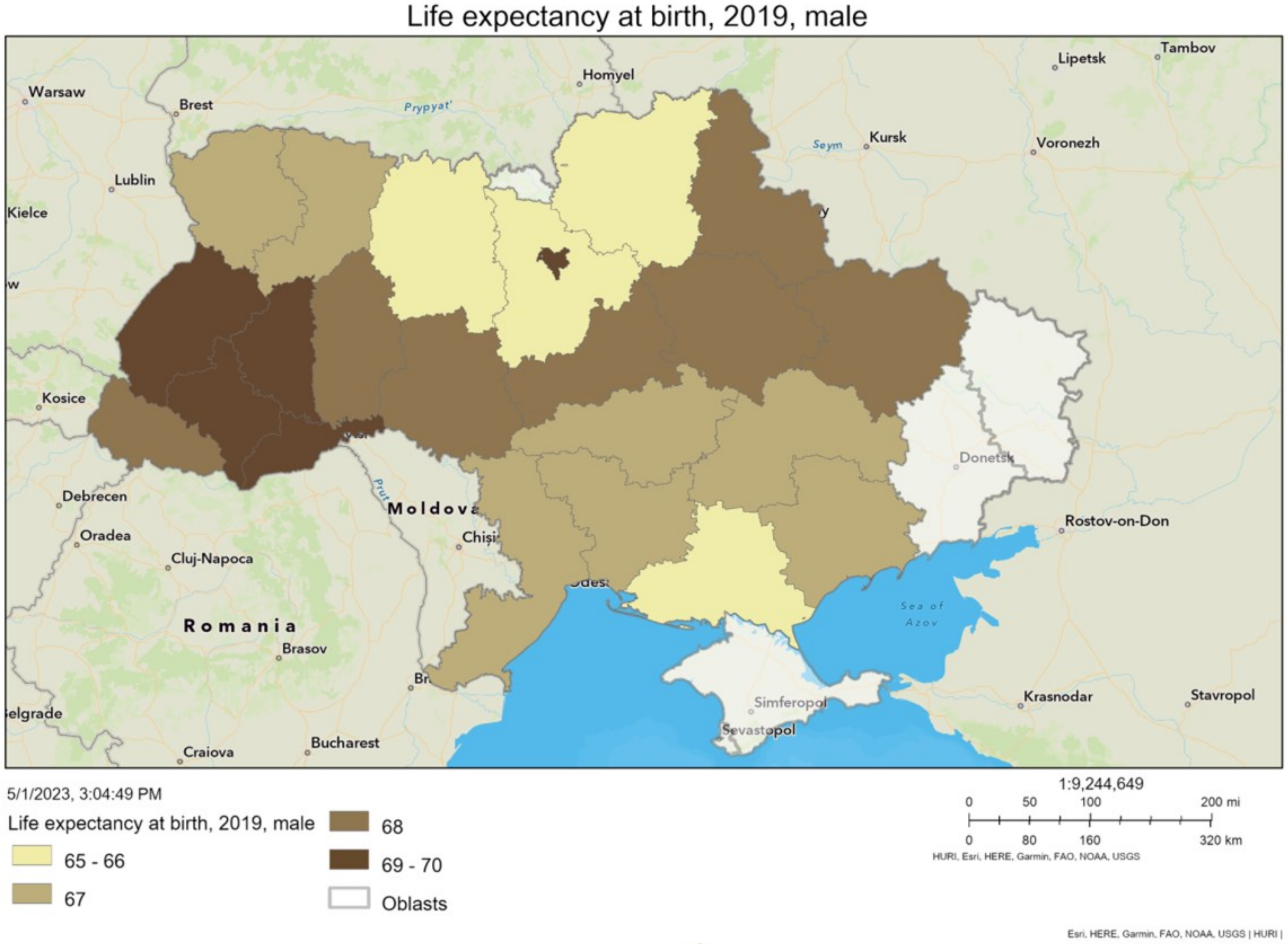
https://twitter.com/i/status/1769061532732731436

Strontium-90 ground deposition density, kBq/m2, 1986



Half-life: 29.1 years
Mode of decay: Beta radiation

Sr-90 can be inhaled, but ingestion in food and water is the greatest health concern. Once in the body, Sr-90 acts like calcium and is readily incorporated into bones and teeth, where it can cause cancers of the bone, bone marrow, and soft tissues around the bone.



3.8-4.0% of all deaths in the contaminated territories of Ukraine from 1990 to 2004 were caused by the Chornobyl catastrophe. The lack of evidence of increased mortality in other affected countries is not proof of the absence of effects from the radioactive fallout.

Since 1990, mortality among liquidators has exceeded the mortality rate in corresponding population groups.

From 112,000 to 125,000 liquidators died before 2005 - that is, some 15% of the 830,000 members of the Chornobyl cleanup teams.

The calculations suggest that the Chornobyl catastrophe has already killed several hundred thousand human beings in a population of several hundred million that was unfortunate enough to live in territories affected by the fallout.

The comparison of Chornobyl and Fukushima Accidents

Nuclear Disaster

Comparison of Estimated Amounts of Released Radionuclides between the Chernobyl NPS Accident and the TEPCO's Fukushima Daiichi NPS Accidents

Nuclides	Half-life[a]	Boiling point[b] ℃	Melting point[c] ℃	Release into the environment: PBq*		TEPCO's Fukushima Daiichi NPS/ Chernobyl NPS
				Chernobyl NPS[d]	TEPCO's Fukushima Daiichi NPS[e]	
Xenon (Xe)-133	5 days	-108	-112	6,500	11,000	1.69
Iodine (I)-131	**8 days**	**184**	**114**	**～1,760**	**160**	**0.09**
Cesium (Cs)-134	**2 years**	**678**	**28**	**～47**	**18**	**0.38**
Cesium (Cs)-137	**30 years**	**678**	**28**	**～85**	**15**	**0.18**
Strontium (Sr)-90	29 years	1,380	769	～10	0.14	0.01
Plutonium (Pu)-238	88 years	3,235	640	1.5×10^{-2}	1.9×10^{-5}	0.0012
Plutonium (Pu)-239	24,100 years	3,235	640	1.3×10^{-2}	3.2×10^{-6}	0.00024
Plutonium (Pu)-240	6,540 years	3,235	640	1.8×10^{-2}	3.2×10^{-6}	0.00018

Ratio of radionuclides accumulated in the reactor core at the time of the accidents that were released into the environment

Nuclides	Chernobyl NPS[f]	TEPCO's Fukushima Daiichi NPS[g]
Xenon (Xe)-133	Nearly 100%	Approx. 60%
Iodine (I)-131	Approx. 50%	Approx. 2-8%
Cesium (Cs)-137	Approx. 30%	Approx. 1-3%

*PBq equals 10^{15}Bq.

Sources: a: ICRP Publication 72 (1996); b and c: Rikagaku Jiten 5th edition (1998); d: UNSCEAR 2008 Report, Scientific Annexes C, D and E; e: Report of Japanese Government to the IAEA Ministerial Conference on Nuclear Safety (June 2011); f: UNSCEAR 2000 Report, ANNEX J; g: UNSCEAR 2013 Report, ANNEX A

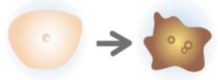
Cesium has a boiling point of 678°C and is therefore in a gaseous state when the nuclear fuel is in a molten state (its melting point is 2,850°C). When cesium in a gaseous state is released into the atmosphere, it goes into a liquid state when the temperature drops below its boiling point, and it further becomes particulate at temperatures below its melting point of 28°C. Thus, cesium is mostly in a particulate form in the atmosphere and will be diffused over wide areas by wind. This was roughly how radioactive cesium was spread to distant areas in the Fukushima Accident.

The larger amount released at the time of the Chornobyl Accident is considered to have been partly due to the fact that the core exploded and was directly exposed to the atmosphere. In contrast, a relatively small amount was released from Fukushima as extensive destruction of the containment vessel was barely avoided, and this is considered to have reduced releases of radioactive materials.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-02-05.html

Effects on Human Body

Classification of Radiation Effects

Categories of effects		Incubation period	e.g.	Mechanism of how radiation effects appear
Categories of effects	**Physical effects**	Within several weeks = Acute effects (early effects)	Acute radiation syndromes*1 Acute skin disease	Deterministic effects (tissue reactions) caused by cell deaths or cell degeneration*2 
		After the lapse of several months = Late effects	Abnormal fetal development (malformation)	
			Opacity of the lens	
			Cancer and leukemia	Stochastic effects due to mutation 
	Heritable effects		Hereditary disorders	

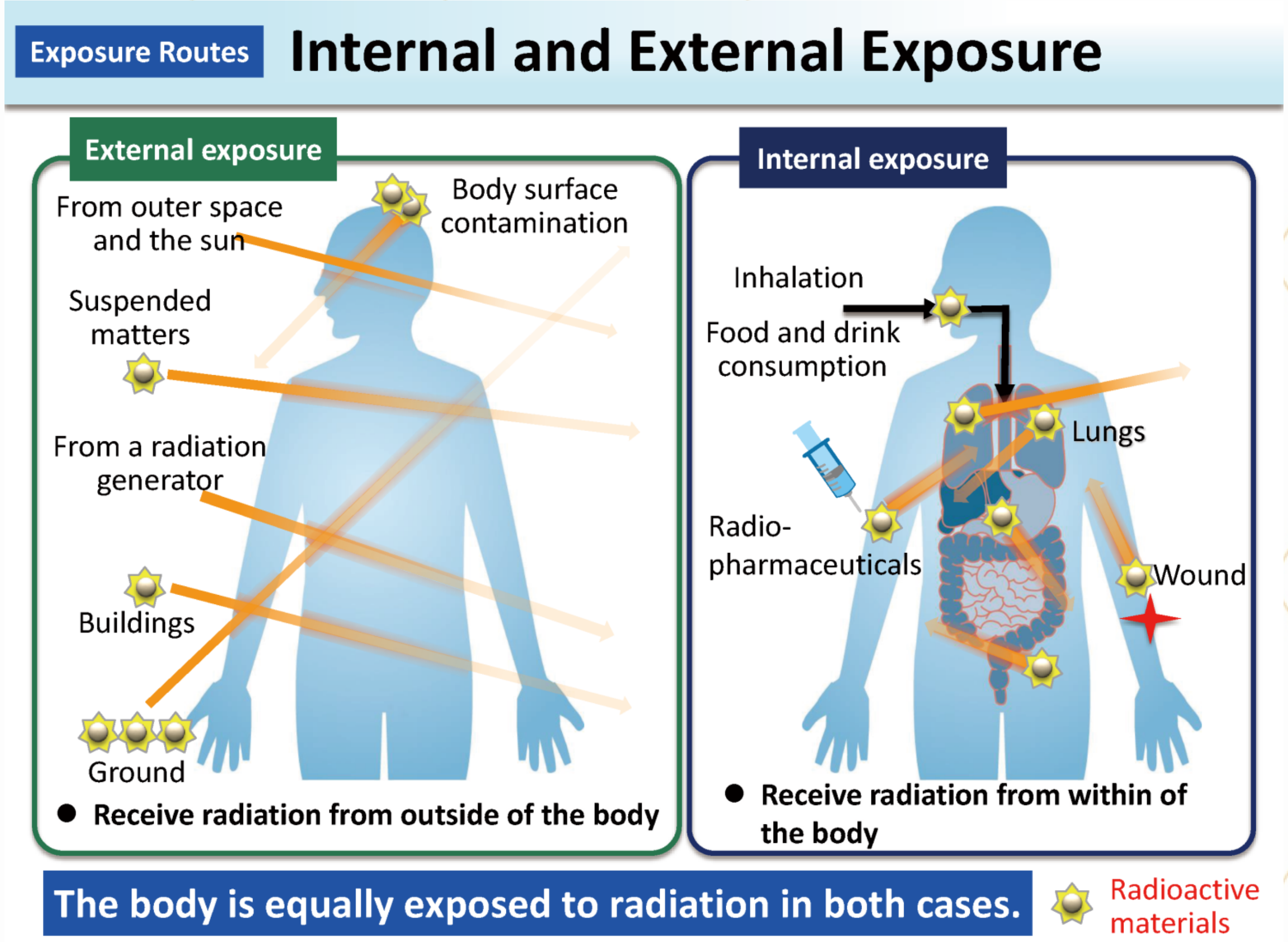
*1: Major symptoms are vomiting within several hours after exposure, diarrhea continuing for several days to several weeks, decrease of the number of blood cells, bleeding, hair loss, transient male sterility, etc.
*2: Deterministic effects do not appear unless having been exposed to radiation exceeding a certain dose level.

Radiation effects are classified into physical effects appearing in a person exposed to radiation and heritable effects appearing in his/her children or grandchildren.

Radiation effects may also be classified depending on the length of time until any symptom appears after exposure. That is, there are acute effects (early effects) that appear relatively early after exposure and late effects that appear after the lapse of several months.

Another classification is based on the difference in mechanisms of how radiation effects appear, i.e., deterministic effects (tissue reactions) and stochastic effects.

Deterministic effects (tissue reactions) are symptoms caused by deaths or degeneration of a number of cells constituting organs and tissues. For example, after exposure to a relatively large amount of radiation, a skin injury or a decrease of the number of blood cells due to deterioration of hemopoietic capacity may occur within several weeks (acute radiation syndrome). Exposure to a large amount of radiation during pregnancy may cause some effects on the fetus and radiation exposure to the eyes may induce cataracts after a while.



Radiation exposure refers to the situation where the body is exposed to radiation.

External exposure means to receive radiation that comes from radioactive materials existing on the ground or in the air or attached to clothes or the surface of the body.

Internal exposure is caused (i) when a person has a meal and takes in radioactive materials in the food or drink (ingestion); (ii) when a person breathes in radioactive materials in the air (inhalation); (iii) when radioactive materials are absorbed through the skin (percutaneous absorption); (iv) when radioactive materials enter the body from a wound (wound contamination); and (v) when radiopharmaceuticals containing radioactive materials are administered for the purpose of medical treatment. Once radioactive materials enter the body, the body will continue to be exposed to radiation until the radioactive materials are excreted in the urine or feces or as the radioactivity weakens over time.

The difference between internal exposure and external exposure lies in whether the source that emits radiation is inside or outside the body. The body is equally exposed to radiation in both cases.

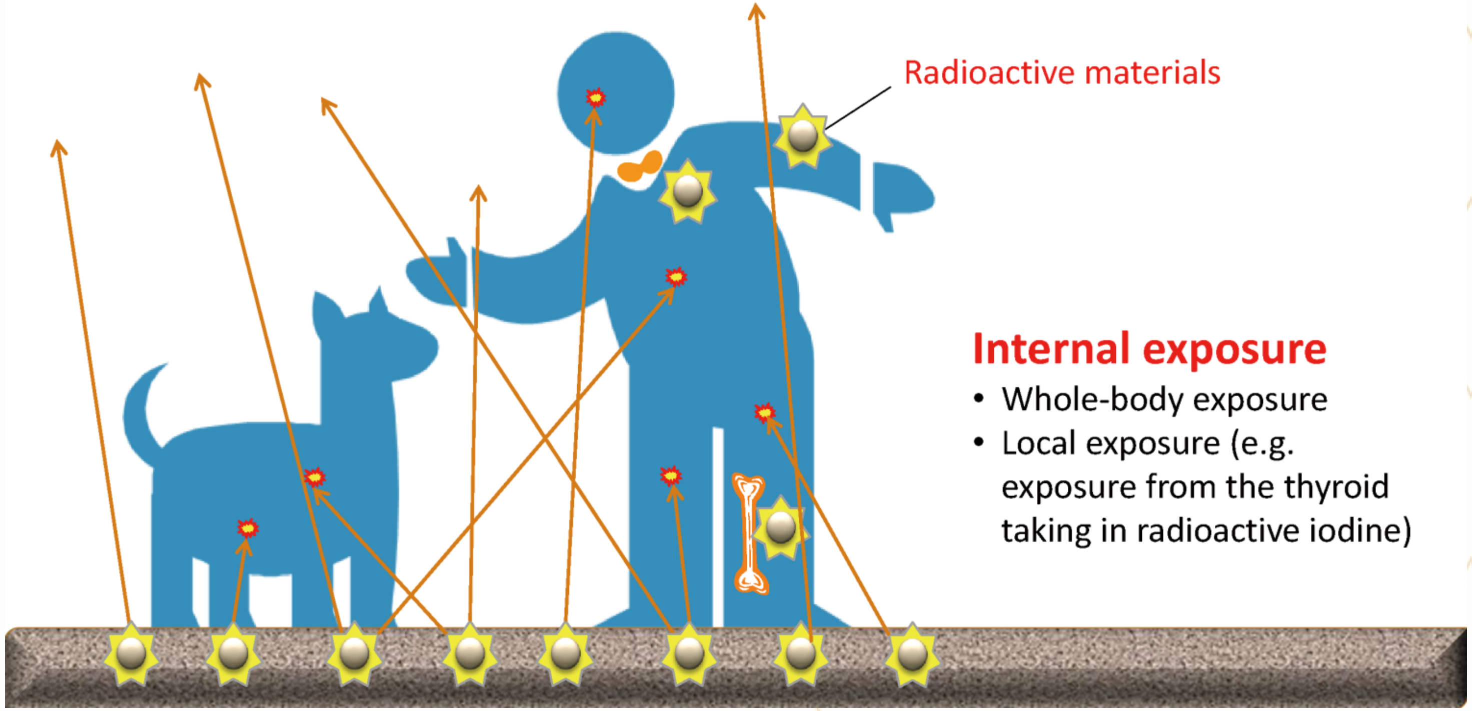
https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-01-01.html

Exposure Routes

Various Forms of Exposure

External exposure

- Whole-body exposure
- Local exposure (e.g. exposure by X-ray examination or local body surface contamination)



Internal exposure

- Whole-body exposure
- Local exposure (e.g. exposure from the thyroid taking in radioactive iodine)

Whole-body exposure refers to exposure of the entire body to radiation, while *local exposure* refers to exposure of a part of the body to radiation.

In whole-body exposure, all the organs and tissues may be affected by the radiation, while in *local exposure* the effects are confined to the exposed organs and tissues. If any organ of the immune system or endocrine system is included in the part exposed, distant organs or tissues could be indirectly affected, but the main concern is basically with the effects on the exposed organs and tissues.

Organs differ in sensitivity to radiation.

In local exposure, therefore, the extent of the effects varies greatly depending on whether the exposed part includes organs that are highly sensitive to radiation.

In internal exposure, organs and tissues where radioactive materials are likely to accumulate will receive high doses of radiation. If such organs and tissues that are prone to accumulation have high sensitivities to radiation, they are more likely to be affected by the radiation

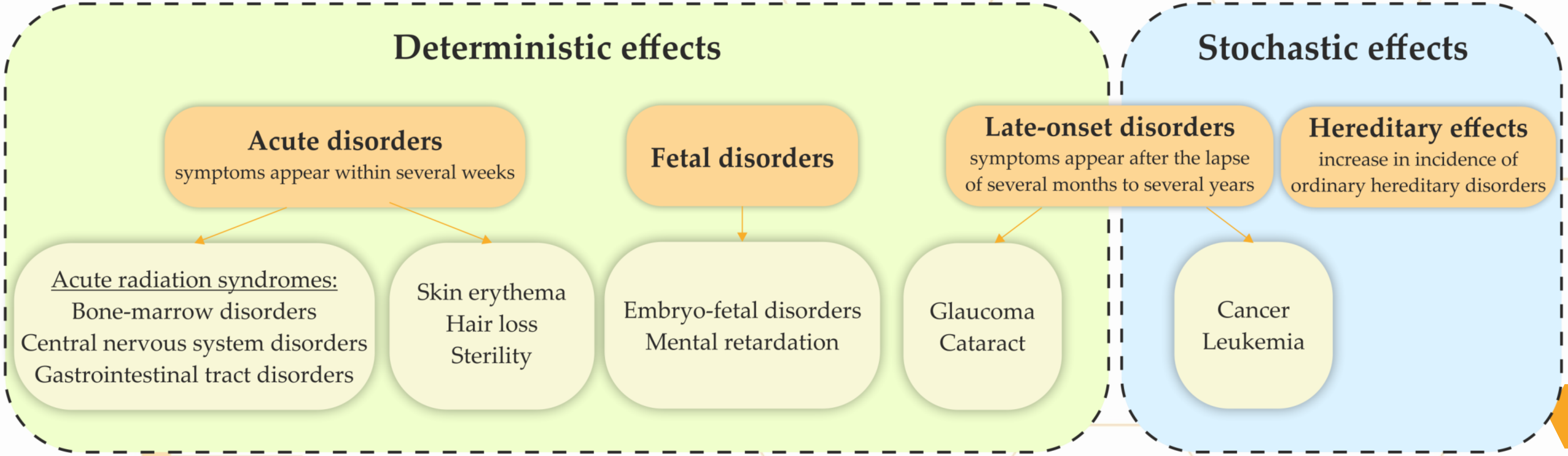
https://www.env.go.jp/en/chemi/rhm/basic-info/1st/02-01-02.html

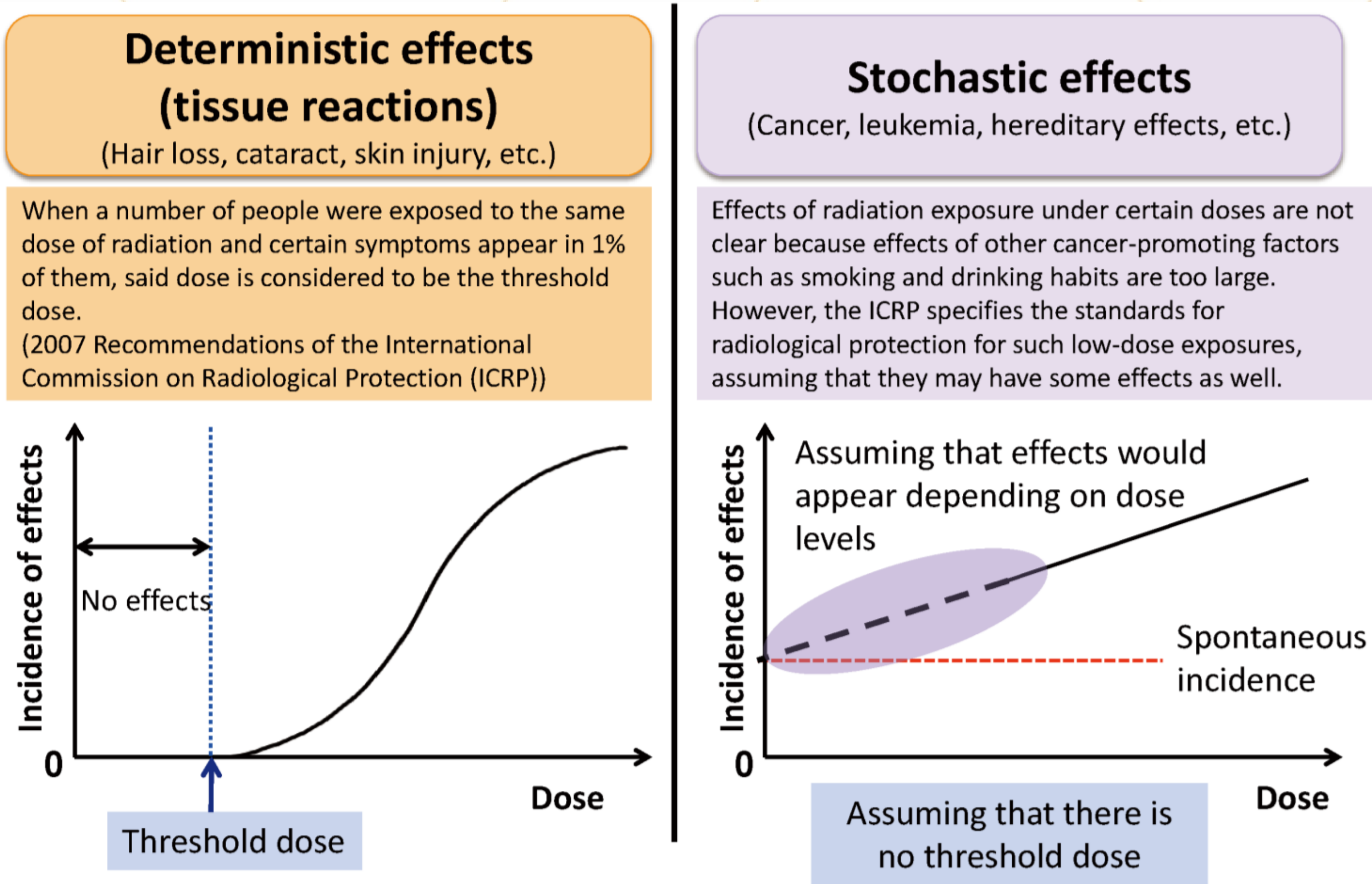
When considering health effects of radiation on human body, one method is to separately consider stochastic effects and deterministic effects (tissue reactions).

Deterministic effects (tissue reactions) do not appear unless having been exposed to radiation exceeding a certain level. Most of the deterministic effects are categorized into acute disorders whose symptoms appear within several weeks after exposure.

Stochastic effects are effects, whose incidence cannot be completely denied even with low-dose exposure. Exposure doses are managed on the safe side in general under the assumption that there is no threshold value.

However, it has not been confirmed that hereditary disorders due to radiation exposure appear among human beings at the same frequencies as estimated from the results of tests on laboratory animals.





Non stochastic effects / Deterministic

- Have definite threshold levels of radiation dose.
- The probability of the effects is proportional to the dose.
- A latent period is seen between the time of exposure and the events to manifest.
- Severity may be proportional to the dose received.
- Seen when the cells are killed or loose capability to divide.

Stochastic Effects / Probablistic

- Have no threshold levels of radiation dose.
- The probability of the effects is proportional to the dose.
- A latent period is seen between the time of exposure and the events to manifest
- Severity is independent of dose received
- Seen when the cells are modified rather than killed.

One of the characteristics of the *deterministic effects* (tissue reactions) is the existence of the threshold dose, which means that exposure to radiation under this level causes no effects but exposure to radiation above this level causes effects. Radiation exposure above the threshold dose causes deaths or degeneration of a large number of cells at one time and the incidence rate increases sharply.

On the other hand, in radiological protection, it is assumed that there is no threshold dose for *stochastic effects*. Under this assumption, the possibility that radiation exposure even at extremely low doses may exert some effects can never be eliminated. It is very difficult to epidemiologically detect stochastic effects due to radiation exposure at low doses below the range of 100 to 200 mSv.

These are primarily two types of stochastic effects:

1. Carcinogenesis
2. Hereditary effects

Both have:

- A random nature of appearance.
- No threshold dose for appearance.
- Definite latent period for appearance after exposure.
- Probability of induction increases with the dose received.
- Severity of the effect is independent of the dose received.
- A risk that can be defined on epidemiological studies only.

Radiation induced carcinogenesis

- Relative risk of radiation induced cancers is a linear function of doses up to 2 Sv.
- At lower dose range of 0-0.5 Sv risks are slightly higher than the extrapolated risk.
- Risk of radiation induced cancers varies with age with patients at younger age being more susceptible.
- Females < 15 years are most susceptible.

Risk estimates for carcinogenesis

- Cancer accounts for ~ 25% of all deaths in developed nations
- For each radiation induced cancer 13-15 years of life will be lost (but most will occur at ages of 68-70 yrs)

Population	High Dose, High Dose Rate	Low Dose, Low Dose Rate
Working population	8×10^{-2} per Sv	4×10^{-2} per Sv
Whole population	10×10^{-2} per Sv	5×10^{-2} per Sv

- Radiation induced hereditary effects are secondary to mutations which are passed on to the progeny.
- Radiation does not cause new types of mutations but increases the frequency of naturally occurring mutations.
- Three classes of hereditary effects are known:
  - Gene mutations
  - Chromosomal aberrations (Down's Syndrome)
  - Multifactorial (Neural tube defects)
- ICRP estimates that risk of hereditary effects due to radiation exposure is:
  - 0.2% per Sv in general population
  - 0.1% per Sv in working population
- Radiosensitivity of different mutations vary widely - so an average mutation risk is considered.
- Low dose rate radiation is less effective in inducing mutations.
- Time interval between exposure and conception plays an important protective role.
- A period of 6 months is therefore recommended between radiation exposure and conception.
- Radiation induced mutations can be transmitted across the generations.
- Average "doubling dose" for humans is considered to be 1.56 Sv.

Disease Class	Base frequency per million live births	First generation risk per million live	2nd generation risk per million live births
Mendelian mutations	16500	750 - 1500	1300 - 2500
Chronic multifactorial diseases	65000	250 - 1200	250 -1200
Congenital abnormalities	60000	2000	2400 - 3000
Total	738000	3000 - 4700	3950 - 6700
Total risk per Gy	NA	0.41 - 0.64 %	0.53 - 0.91 %

Fetal effects:

- Radiation risks to fetus are related to:
  - Exposure magnitude.
  - Time of pregnancy.
- Radiation risks are most significant during organogenesis and in the early fetal period.
- Threshold for malformations:
  - 100 - 200 mGy (Malformations)
  - 100 mGy (Mental Retardation): Risk coefficient is 0.4 per Sv
- An exposure 1 mSv is safe for a fetus - normal exposure from background radiation
- A dose > 0.1 Sv is considered the threshold beyond which an MTP should be considered

Time of radiation vs effect:

- 2-3 weeks: Most embryos are aborted
- 4 - 11 weeks: Severe abnormalities in most organs
- 11-16 weeks: Mental retardation and stunting more common
- 16-25 weeks: Mild degree of mental retardation and microcephaly
- > 30 weeks: Usually leads to functional disabilities in later life

Carcinogenesis:

- Most exposures implicated occur in 3rd trimester
- Doses more than 1 mSv will increase the risk - but no threshold apparent.
- Excess absolute risk is 6% per Sv

Principles of Radiological Protection

Exposure Situations and Protection Measures

People's exposure to radiation

Planned exposure situations	Existing exposure situations	Emergency exposure situations
Situations where protection measures can be planned in advance and the level and range of exposure can be reasonably forecast	Situations where exposure has already occurred as of the time when a decision on control is made	Contingency situations where urgent and long-term protection measures may be required
Dose limits (Public exposure) 1 mSv/year (Occupational exposure) 100 mSv/5 years and 50mSv/year	**Reference level** A lower dose range within 1 to 20 mSv/year, with a long-term goal of 1 mSv/year	**Reference level** Within 20 to 100 mSv/year
Measures Manage disposal of radioactive waste and long-lived radioactive waste	**Measures** Ensure voluntary efforts for radiological protection and cultivate a culture for radiological protection	**Measures** Evacuate, shelter indoors, analyze and ascertain radiological situations, prepare monitoring, conduct health examinations, manage foods, etc.

mSv: millisieverts

Source: Prepared based on the ICRP Publication 103, "The 2007 Recommendations of the International Commission on Radiological Protection" (ICRP, 2007)

The International Commission on Radiological Protection (ICRP) categorizes exposure situations into normal times that allow planned control (planned exposure situations), emergencies such as an accident or nuclear terrorism (emergency exposure situations), and the recovery and reconstruction period after an accident (existing exposure situations) and sets up protection standards for each of them.

In normal times, protection measures should aim to prevent any exposure that may cause physical disorders and to reduce risks of developing cancer in the future as low as possible. The dose limit for public exposure is set at 1 mSv per year, requiring proper management of places where radiation or radioactive materials are handled to ensure that annual public exposure doses do not exceed this level. For workers who handle radiation, the dose limit is set at 100 mSv per five years.

Principles of Radiological Protection

Exposure Situations and Protection Measures

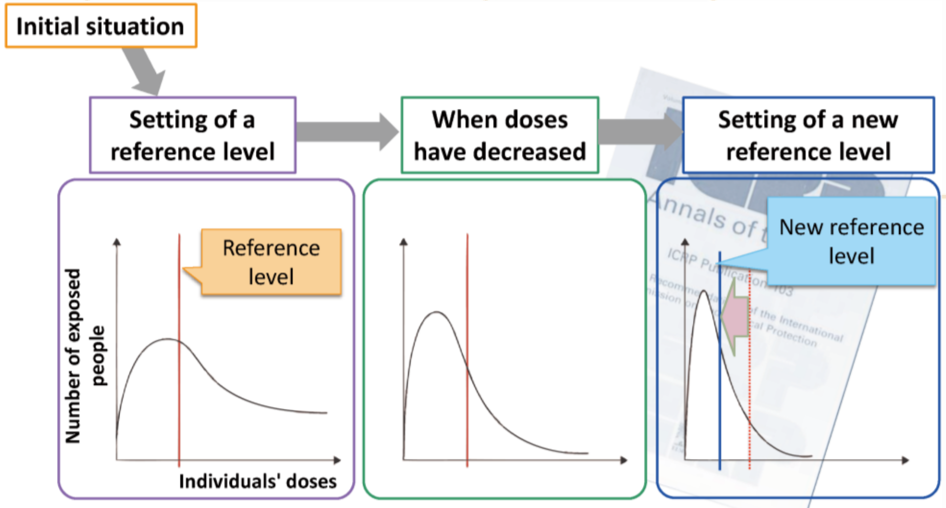
People's exposure to radiation

Planned exposure situations	Existing exposure situations	Emergency exposure situations
Situations where protection measures can be planned in advance and the level and range of exposure can be reasonably forecast	Situations where exposure has already occurred as of the time when a decision on control is made	Contingency situations where urgent and long-term protection measures may be required
Dose limits (Public exposure) 1 mSv/year (Occupational exposure) 100 mSv/5 years and 50mSv/year	**Reference level** A lower dose range within 1 to 20 mSv/year, with a long-term goal of 1 mSv/year	**Reference level** Within 20 to 100 mSv/year
Measures Manage disposal of radioactive waste and long-lived radioactive waste	**Measures** Ensure voluntary efforts for radiological protection and cultivate a culture for radiological protection	**Measures** Evacuate, shelter indoors, analyze and ascertain radiological situations, prepare monitoring, conduct health examinations, manage foods, etc.

mSv: millisieverts

Source: Prepared based on the ICRP Publication 103, "The 2007 Recommendations of the International Commission on Radiological Protection" (ICRP, 2007)

In an emergency such as a nuclear accident (emergency exposure situations), physical disorders that would never be seen in normal times may develop, priority should be placed on measures to prevent serious physical disorders rather than on measures to be taken in normal times (to reduce risks of developing cancer in the future). Reference level of 20 to 100 mSv/year is set for the public instead of applying dose limits and efforts to reduce exposure doses are required. For people who are engaged in emergency measures or rescue activities, a level of 1,000 or 500 mSv may sometimes be adopted as a rough indication depending on the circumstances.



Source: Prepared based on the ICRP Publication 103, "The 2007 Recommendations of the International Commission on Radiological Protection" (ICRP, 2007)

Then, in the recovery and reconstruction period (existing exposure situations), a reference level is to be set within the range of 1 to 20 mSv/year, which is lower than the reference level in an emergency but higher than the dose limits applicable in normal times.

Dose Reduction

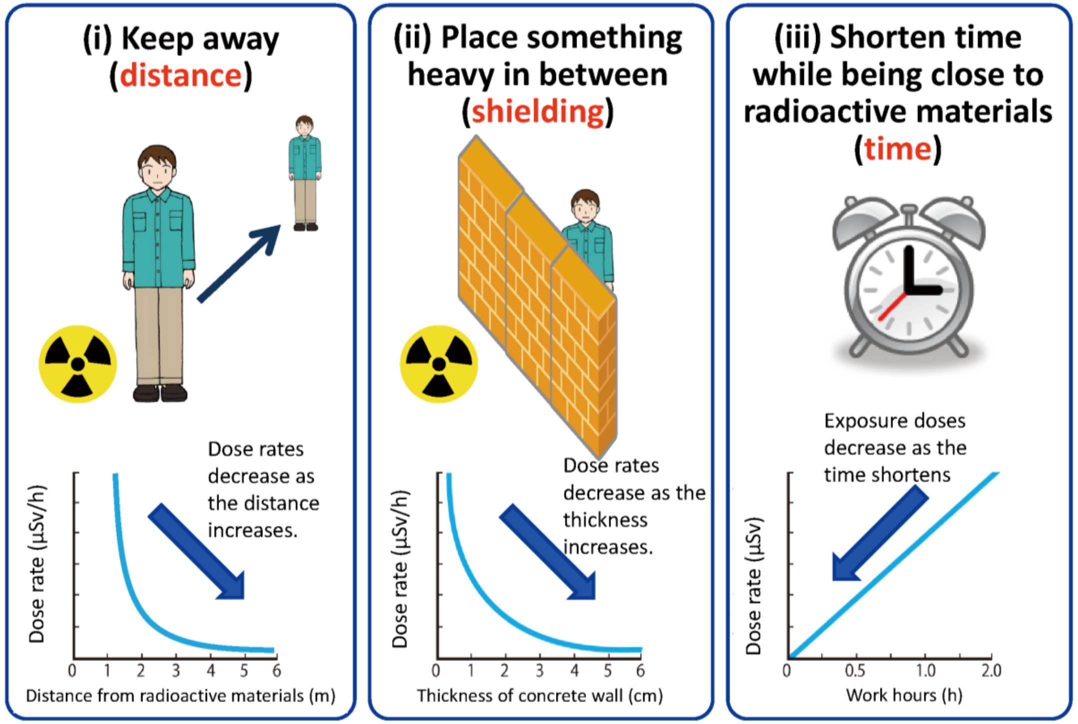
Internal Exposure - Responses Immediately after a Nuclear Hazard -

- ◯ Prevent radioactive materials from entering the body through the mouth, nose or wounds, in principle.
- ◯ Be careful not to lose nutritional balance, being excessively worried about a small amount of radioactive materials below the standard limit.
- ◯ Be aware of information on the release of radioactive materials.
- ◯ Wash off soil immediately from the body, shoes and clothes.

As causes of internal exposure, both inhalation and ingestion of foods need to be taken into consideration.

Example - when calculating exposure doses for children engaging in outdoor activities at places with high ambient doses, doses due to internal exposure account for only around 2% to 3% and exposure doses are mostly due to radiation from outside of the body. Therefore, people do not have to be too nervous about exposure through inhalation and proper daily hygienic control (taking a bath, getting a haircut, washing hands, cleaning, and doing the laundry, etc.) is effective in reducing internal exposure to some extent.

Regarding the possibility of internal exposure caused by ingestion of foods, attention needs to be paid to foods from which radioactive cesium is detected at high levels. In particular, special attention is required for ferns and mushrooms, which have a property to concentrate cesium.



Limiting Time. The amount of radiation exposure depends directly (linearly) on the time people spend near the radiation source, and the dose can be reduced by limiting exposure time.

Distance. The amount of radiation exposure depends on the distance from the radiation source. Like heat from a fire, if you are too close, the intensity of heat radiation is high, and you can get burned. If you are at the right distance, you can withstand there without any problems and are comfortable. If you are too far from the heat source, the insufficiency of heat can also hurt you. In a certain sense, this analogy can be applied to radiation also from radiation sources.

Shielding. Finally, if the source is too intensive and time or distance does not provide sufficient radiation protection, the shielding must be used. Radiation shielding usually consists of barriers of lead, concrete, or water. Many materials can be used for radiation shielding, but there are many situations in radiation protection. It depends on the type of radiation to be shielded, its energy, and many other parameters. For example, even depleted uranium can be used as good protection from gamma radiation, but on the other hand, uranium is absolutely inappropriate for shielding neutron radiation.

Principles of Radiological Protection

International Commission on Radiological Protection (ICRP)

International Commission on Radiological Protection (ICRP)

The Commission aims to make recommendations concerning basic frameworks for radiological protection and protection standards. The Commission consists of the Main Commission and four standing Committees (radiation effects, doses from radiation exposures, protection in medicine, and application of the Commission's recommendations).

(Reference) Dose limits excerpted from ICRP Recommendations

	1977 Recommendations	1990 Recommendations	2007 Recommendations
Dose limits (occupational exposure)	50 mSv/year	100 mSv/5 years and 50 mSv/year	100 mSv/5 years and 50 mSv/year
Dose limits (public exposure)	5 mSv/year	1 mSv/year	1 mSv/year

mSv: millisieverts

The International Commission on Radiological Protection (ICRP) is an independent, international, non-governmental organization, with the mission to protect people, animals, and the environment from the harmful effects of ionizing radiation.

- The concept of a 'reference human' to help manage the many different situations in which human beings would or could be exposed to ionizing radiations.
- ICRP published comprehensive report on Reference Man in 1975 (ICRP, 1975) - recent revision is in ICRP 2002.
- The purpose of Reference Man was to create points of reference (or 'benchmarks') for the procedure of dose estimations, for considering the relationships between doses to different parts of the human body and their effects, and for the derivation of relevant quantities (equivalent dose and effective dose) and units for their interpretation in the context of human radiological protection.
- Most countries have modified the concept of reference man - e.g. Indian Reference Man

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/04-01-02.html

Principles of Radiological Protection

Three Fundamental Principles of Radiological Protection

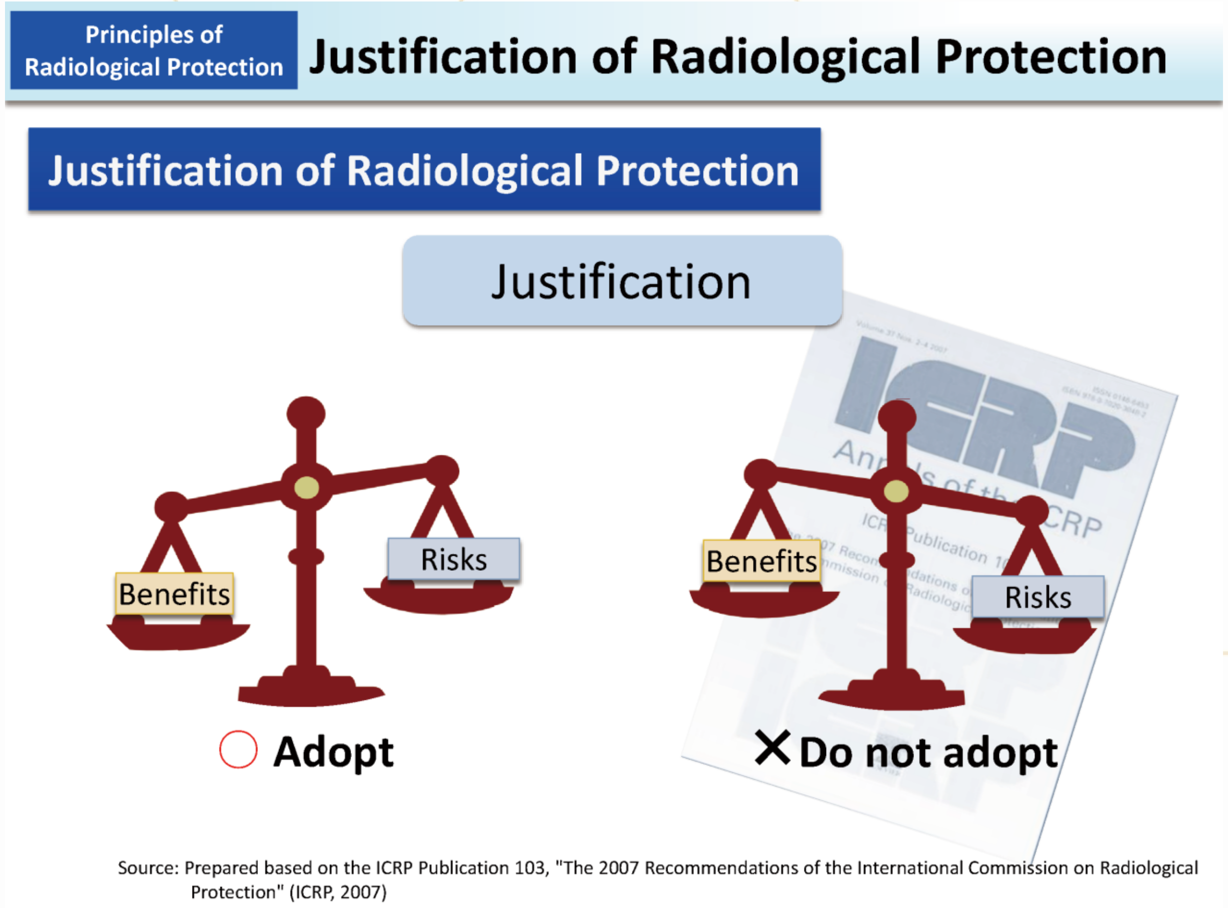
ICRP's three fundamental principles of radiological protection

- **Justification**
- **Optimization**
- **Application of dose limits**

Source: ICRP Publication 103, "The 2007 Recommendations of the International Commission on Radiological Protection" (ICRP, 2007)

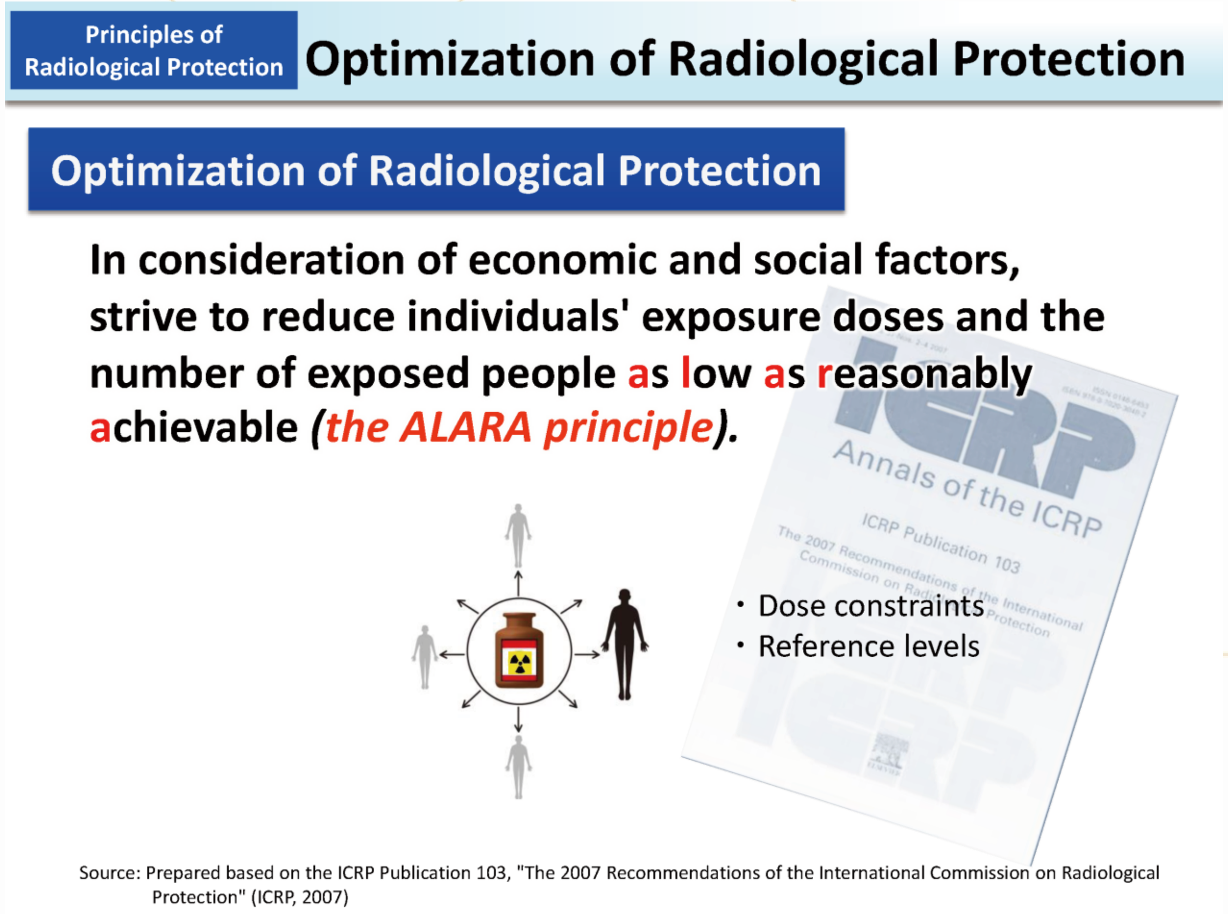
The protection level is considered based on the idea that risks cannot be completely eliminated and on an assumption that such risks can be tolerated.

This is the very basis of the principles of radiological protection, placing emphasis on the "justification," "optimization" and "application of dose limits".



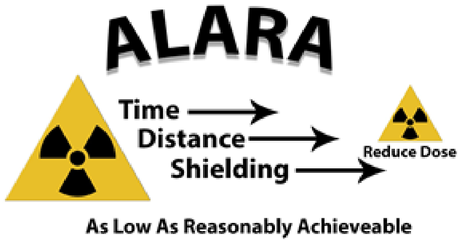
The first principle is the justification of radiological protection. This is the fundamental principle that an act of using radiation is permitted only when the benefits or merits outweigh the radiation risks.

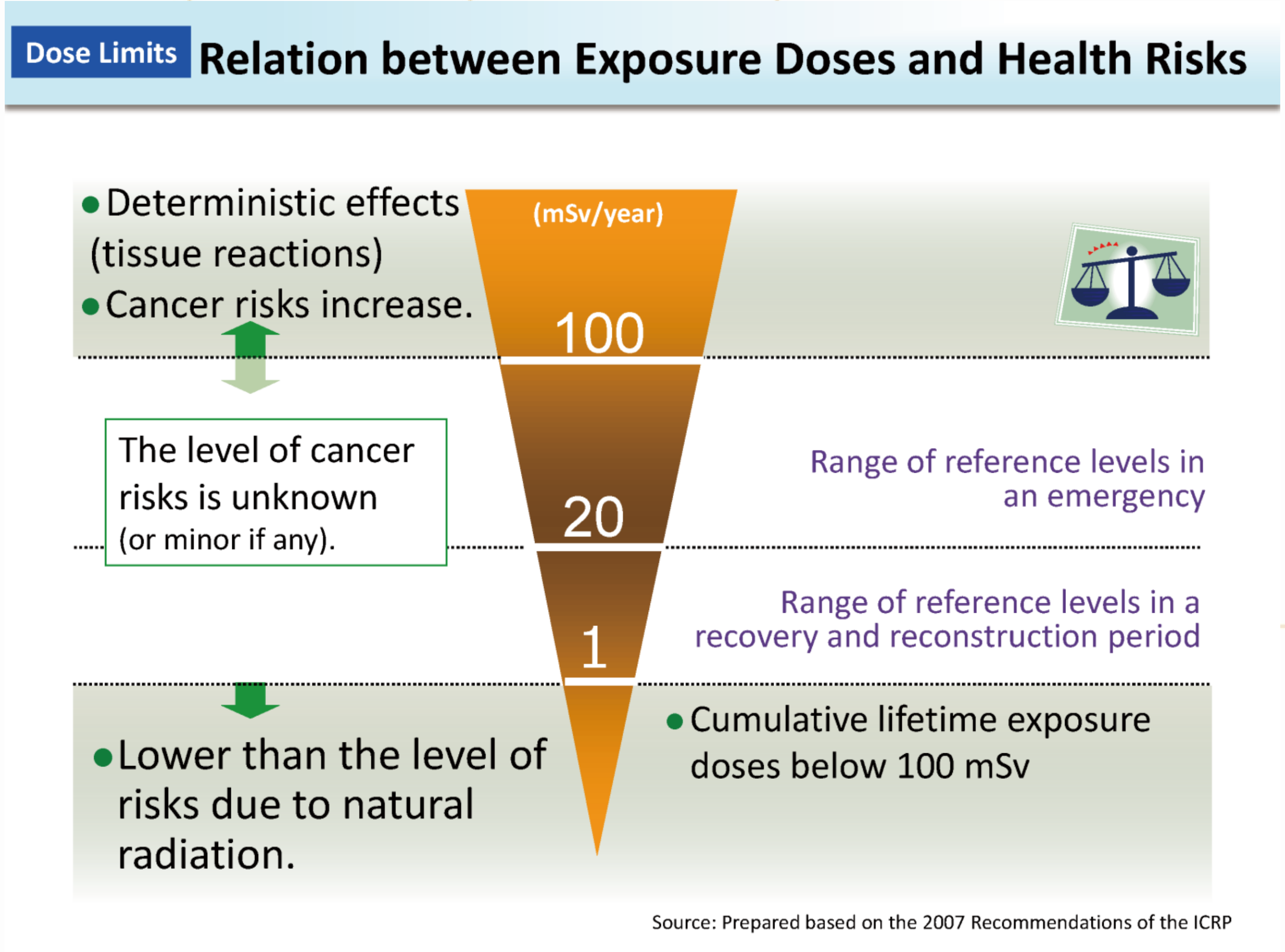
This principle is applied not only to acts of using radiation but also to all activities that bring about changes in exposure situations. In other words, this is also applied to emergency exposure situations and existing exposure situations, as well as to planned exposure situations. For example, justification is required even in the case of considering decontamination of contaminated areas.



The second principle is the optimization of radiological protection. When merits of an act of using radiation outweigh radiation risks, it is decided to use radiation by taking measures to reduce exposure doses as low as reasonably achievable. This is called the ALARA principle. The optimization of radiological protection means to strive to reduce exposure doses as low as possible, while taking into consideration social and economic balances, and does not necessarily mean to minimize exposure doses.

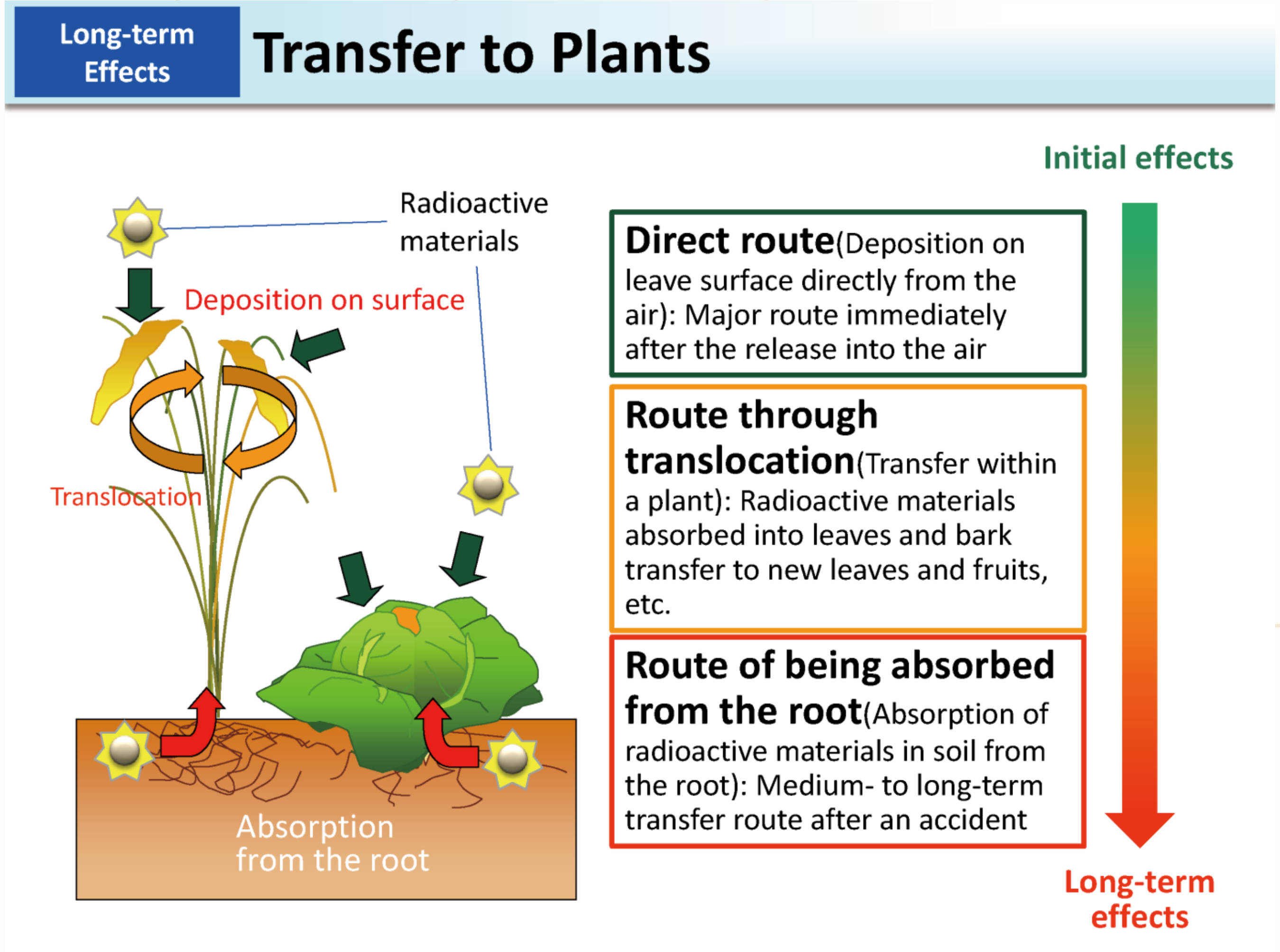
In order to promote the optimization of radiological protection, dose constraints and reference levels are utilized. Reference levels are adopted as indicators to limit individuals' doses from specific radiation sources in decontamination work, for example.





There is scientific evidence for the fact that radiation doses of 100 to 200 mSv or over in a relatively short time increase deterministic effects (tissue reactions) and cancer risks. Therefore, in an emergency due to a radiation accident, the initial reference level is set to avoid annual exposure doses of 100 mSv or over in order to prevent serious physical disorders. When the situation improves as the accident is brought under control and there is almost no one who receives a high dose exceeding the initial reference level, a new lower reference level (such as 1 to 20 mSv per year) is set to curb increases in risks of any possible cancer in the future, thereby further promoting exposure dose reduction.

As the standard limit in normal times, 1 mSv/year is adopted. As a result, some misunderstand that radiation exposure exceeding 1 mSv per year is dangerous or that they may be exposed to radiation up to that level. However, dose limits do not represent the threshold dividing the safety and the danger.



As Cs-137 has a long half-life of 30 years, once released into the environment due to an accident at a nuclear power station or other reasons, its effects may be prolonged. There are roughly three routes through which radioactive materials in the environment transfer to the edible parts of crops.

The first is the route wherein radioactive materials adhere to the surface of edible parts of crops directly from the air.

The second is the route through translocation. Translocation refers to the phenomenon wherein absorbed nutrients or metabolites produced by photosynthesis are transported from some tissue to another tissue in a plant. Radioactive materials that adhere to leaves or bark are sometimes absorbed and transfer to new leaves and fruits within a plant.

The third is the route wherein radioactive materials in soil are absorbed from the root. After the release of radioactive materials into the air stops, radioactive materials that fell onto farmland will mainly follow this route and will be absorbed into crops from the root.

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/04-04-01.html

Long-term Effects | Distribution of Radioactive Cesium in Soil

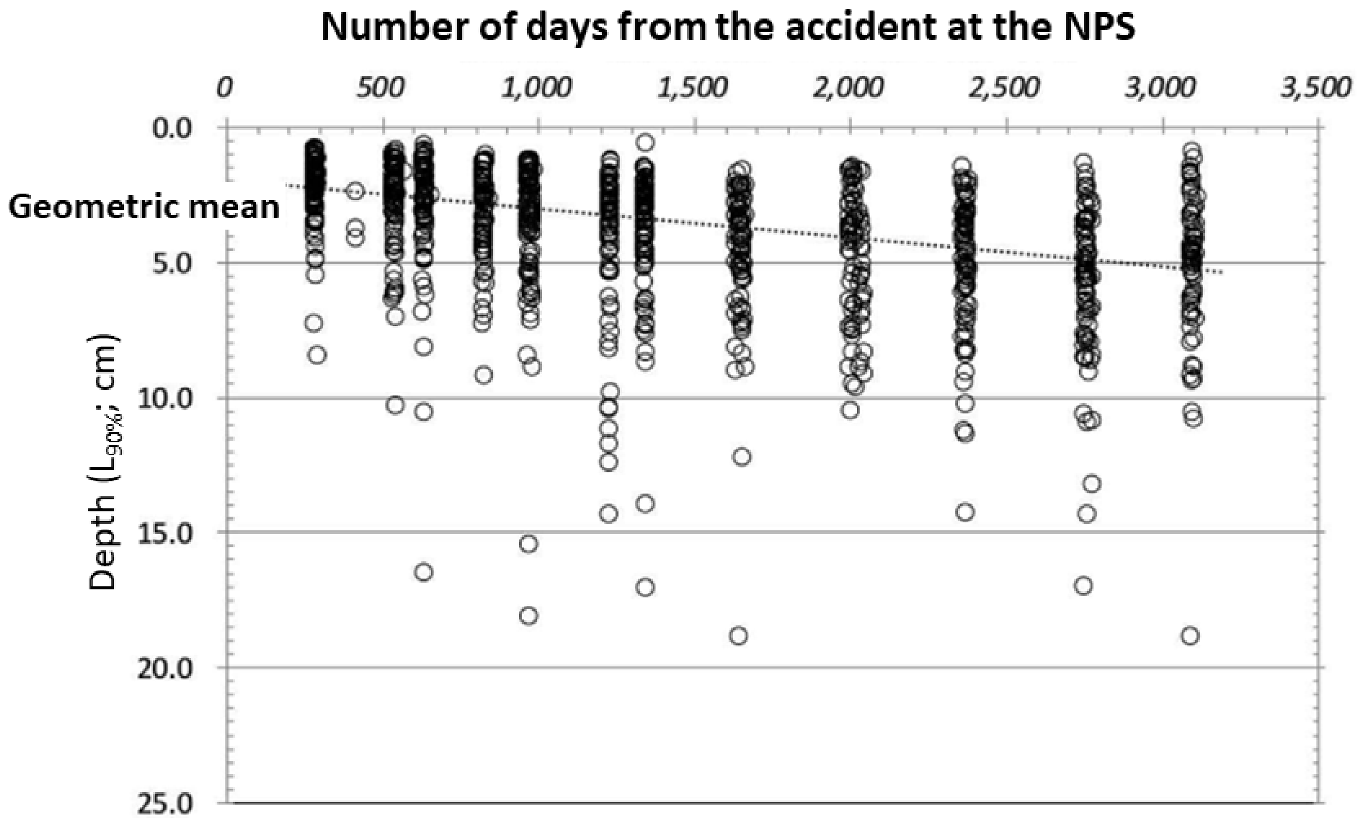


Figure: Data on changes over time in $L_{90\%}$* since December 2011 (85 locations at uncultivated land in Fukushima Prefecture, the southern part of Miyagi Prefecture and the northern part of Ibaraki Prefecture)

(Reference) Depth ($L_{90\%}$): The depth from the ground surface where 90% of all deposited radioactive cesium is contained

Source: Prepared based on the outcome report, "Survey of Depth Distribution of Radioactive Cesium in Soil," of the FY2019 project, "Compilation of Data on Distribution of Radioactive Materials Released due to the Accident at Tokyo Electric Power Company (TEPCO)'s Fukushima Daiichi NPS" commissioned by the Secretariat of the Nuclear Regulation Authority

The survey on effects of the Fukushima Daiichi NPS Accident that occurred in 2011 revealed that the depth from the ground surface containing 90% of all deposited radioactive cesium has been changing gradually over time, and the geometric mean as of September 2019 was 4.6 cm.

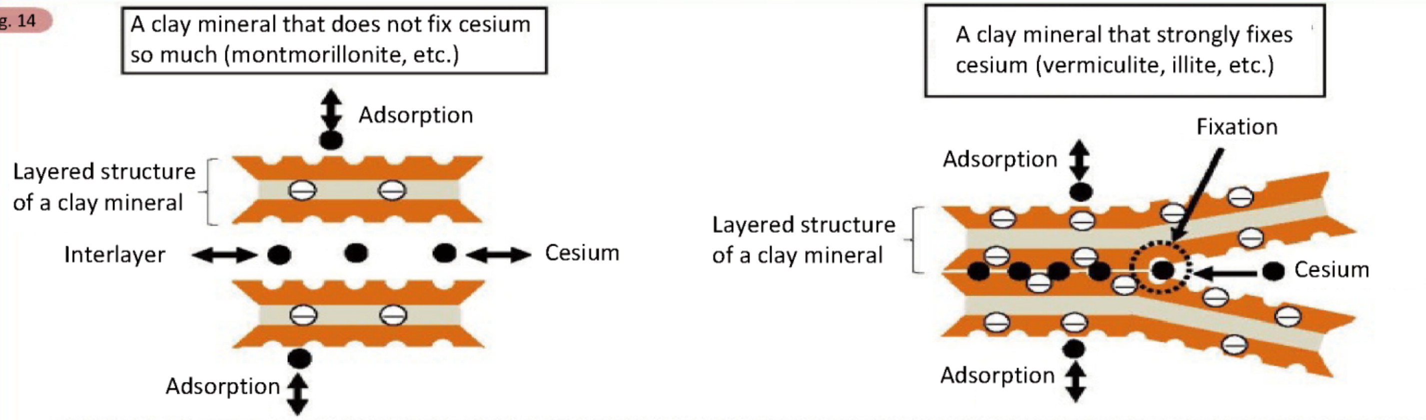
The survey on effects of the Chornobyl NPS Accident that occurred in 1986 revealed that approx. 80% of Cs-137 deposited on soil due to the accident had been staying within 10 cm from the ground surface even after 14 years from the accident

Long-term Effects

Behavior of Radioactive Cesium in the Environment: Adsorption and Fixation by Clay Mineral

Adsorption and fixation of cesium

Fig. 14



[Explanation]

- A clay mineral on its surface has a negative charge and can adsorb cesium and part of the clay mineral can also incorporate and fix cesium in itself over time.
- Adsorbed cesium can be absorbed by plants, but once fixed, not so much is absorbed.

Table 4

Soil components	Adsorption of Cs	Fixation of Cs
Soil organic matters	Strong	Weak
Clay minerals (non-micaceous)		
Kaolinite, Halloysite	Strong	Weak
Allophane, Imogolite	Strong	Weak to medium
Montmorillonite	Strong	Weak
Clay minerals (micaceous)		
Vermiculite	Strong	Strong
Illite	Strong	Medium to strong
Aluminum vermiculite	Strong	Medium to strong
Zeolite	Strong	Strong (Note)

(Note) Anchoring power of these components varies depending on production areas and qualities.

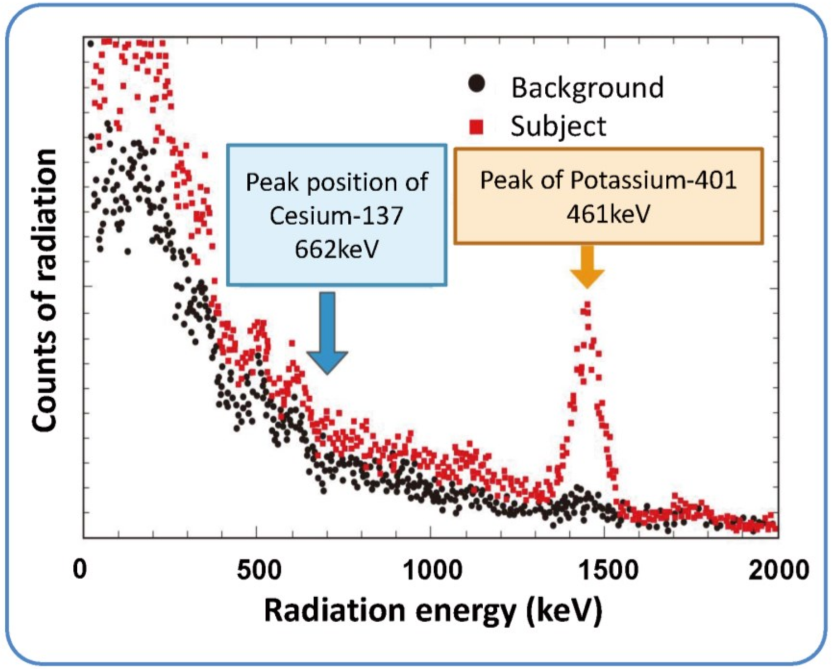
[Explanation]

- Soil organic matters and non-micaceous clay minerals, such as montmorillonite, have weak fixation power.
- Micaceous clay minerals, such as vermiculite and illite, strongly fix cesium.

Cesium has a similar chemical property as potassium, etc. (having a positive charge) and can be easily adsorbed by clay minerals that have a negative charge superficially.

Furthermore, some clay minerals have the ability to fix cesium that they have adsorbed, as time proceeds. It is known that cesium, once fixed, becomes hardly soluble in water.

Whole-body counter



Measure radiation emitted from within the body ⇒ Measure internal radioactivity for each radioactive material

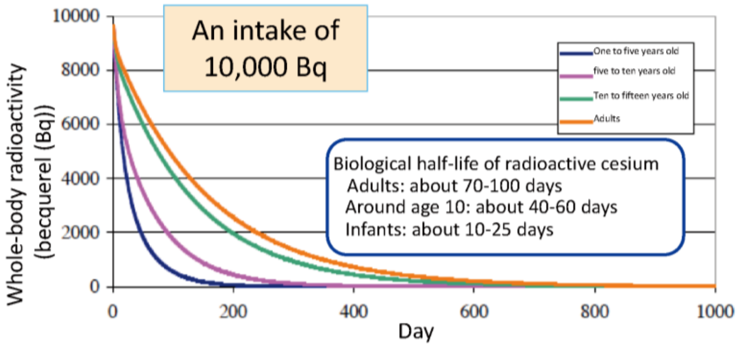
The amount of potassium in the body is around 2 g per 1 kg of body weight, and approx. 0.01% of that amount is radioactive potassium (Potassium-40)

keV: kilo electron volts

Radioactivity of each nuclide can be quantitatively assessed by measuring radiation emitted from within the body using a whole-body counter.

The black round dots in the graph represent values measured while no one is on the bed (background state). When the subject is on the bed, radiation peaks appear, as indicated by the red square dots. The energy of γ-rays is unique for each radioisotope. For example, radioactive potassium, K-40, emits γ-rays with energy of 1,461 keV. Therefore, if such amount of energy is detected, this reveals the existence of K-40 within the body. The gamma-ray energy of Cesium-137 is 662 keV.

While potassium is an element essential to life, approx. 0.01% of all potassium is radioactive. Radioactive potassium is mainly contained in water in cells and is present in muscles but is seldom present in fat cells that contain little water



The younger a person is, the faster the metabolism.

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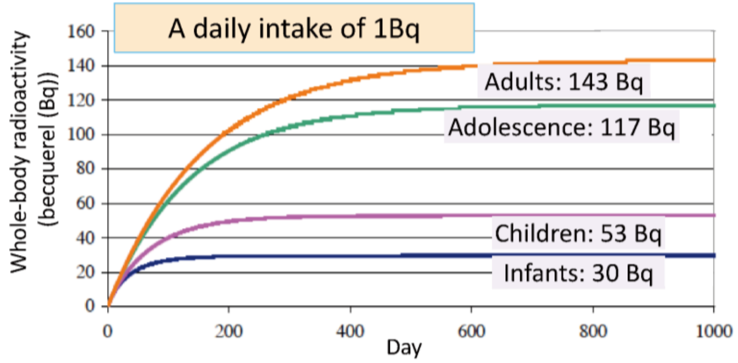
Estimation of initial exposure

- will be effective for no longer than around a year even for adults.
- will be effective for up to around half a year for children.



The younger a person is, the smaller the amount of radioactive materials remaining in the body.

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In estimating additional exposure through ingestion,

- finite values are unlikely to be obtained for children.
- it is more reasonable to examine adults in order to detect trace intake.

Source: Prepared based on a material released for the Japan Society of Radiation Safety Management Symposium in Miyazaki (June 29, 2012)

Whole-body counters (WBCs) can measure the content of radioactivity in a body on the day of measurement. Like other radiation measuring instruments, WBCs have a detection limit depending on their performance and counting time.

As radioactive cesium has a biological half-life of 70-100 days for around one year after the accident would be the time limit for estimation of the initial body burden (in the case of a single intake event). The radioactivity of cesium incorporated into the body decreases in around a year to nearly zero, namely the level before the intake. Subsequent whole-body counting is performed for the purpose of estimating chronic exposure, mainly from foods.

In contrast, whole-body counting for children is likely to result in values lower than the detection limit because a trace amount of the initial intake can be observed for only around half a year and the residual radioactivity in the body accumulated by chronic intake is also small due to the rapid metabolism of children. In such cases, it would rather be reasonable to examine adults and estimate their internal doses in terms of understanding the internal exposure situation in detail, taking into account the fact that the committed effective dose coefficients are similar for both children and adults even though their metabolism rates are quite different.

Radionuclides with short effective half-lives, such as I-131, cannot be detected by WBC or other radiation measurement equipment after their decay out. Pure beta-emitters that do not emit γ-rays, such as Sr-90, also cannot be detected by a WBC.

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