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BRIN-JAEA FOLLOW-UP TRAINING COURSE ON
ENVIRONMENTAL RADIOACTIVITY MONITORING

Environmental Behavior of Radionuclides

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Tangerang Selatan, 14 October 2025

Curriculum Vitae

Ambar Winansi

- Education : STTN-BATAN – Nuclear Technophysics
  UI – Environmental Engineering
- Working Experience :

2014-2020	: Environmental Radioactivity Monitoring and Emergency Section – Personnel Dose and Environmental Monitoring Division
2021-2023	: Serpong Radiation Laboratory
2024	: Laboratory of Energy Resources, Fuels, and Environment
2025	: Research Center for Safety, Metrology, and Nuclear Quality Technology (PRTKMMN)

- Training
  - Advanced Instructor Training Course on Environmental Radioactivity Monitoring (2021)
  - Nuclear Technology Seminar on Nuclear Energy Officials (2021)
  - Instructor Training Course on Environmental Radioactivity Monitoring (2023)

Contents

Objectives

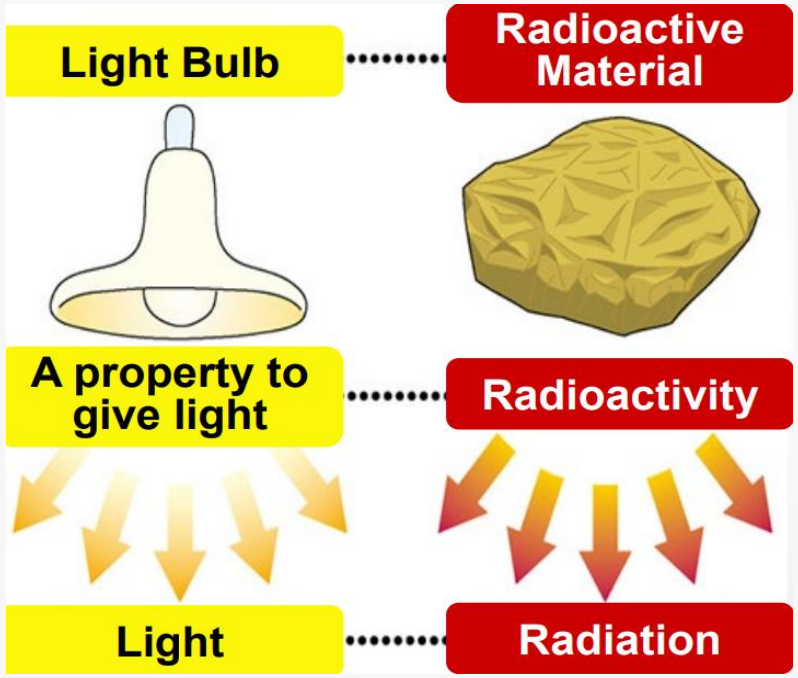
1. **Understand the fundamental principles** governing the behavior, movement, and transformation of radionuclides in different environmental compartments — atmosphere, water, soil, sediment, and biota.

2. **Enhance participants' ability to assess environmental radiation risks** by analyzing radionuclide pathways, transfer mechanisms, and influencing physical–chemical factors

3. **Develop competence in using environmental transport and transfer models** for predicting radionuclide dispersion, accumulation, and bioavailability in environmental media and food chains.

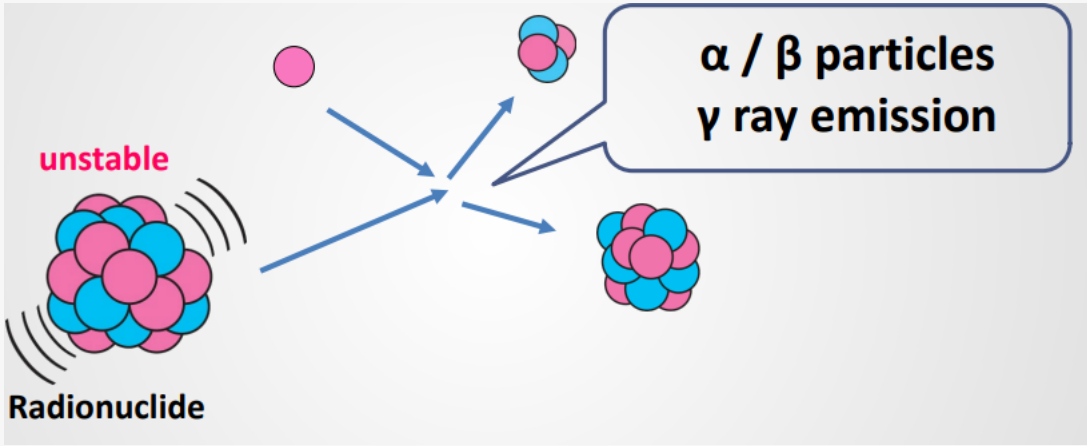
Definition and Relevance in Radiation Protection and Environmental Assessment

Radioactive Material, Radioactivity, and Radiation



A material emitting radiation

The emitting property



Radionuclides emits radiations during radioactive decay
An unstable nucleus spontaneously decomposes to form a different nucleus, giving off radiation in the form of particles or high energy rays.

Radiation

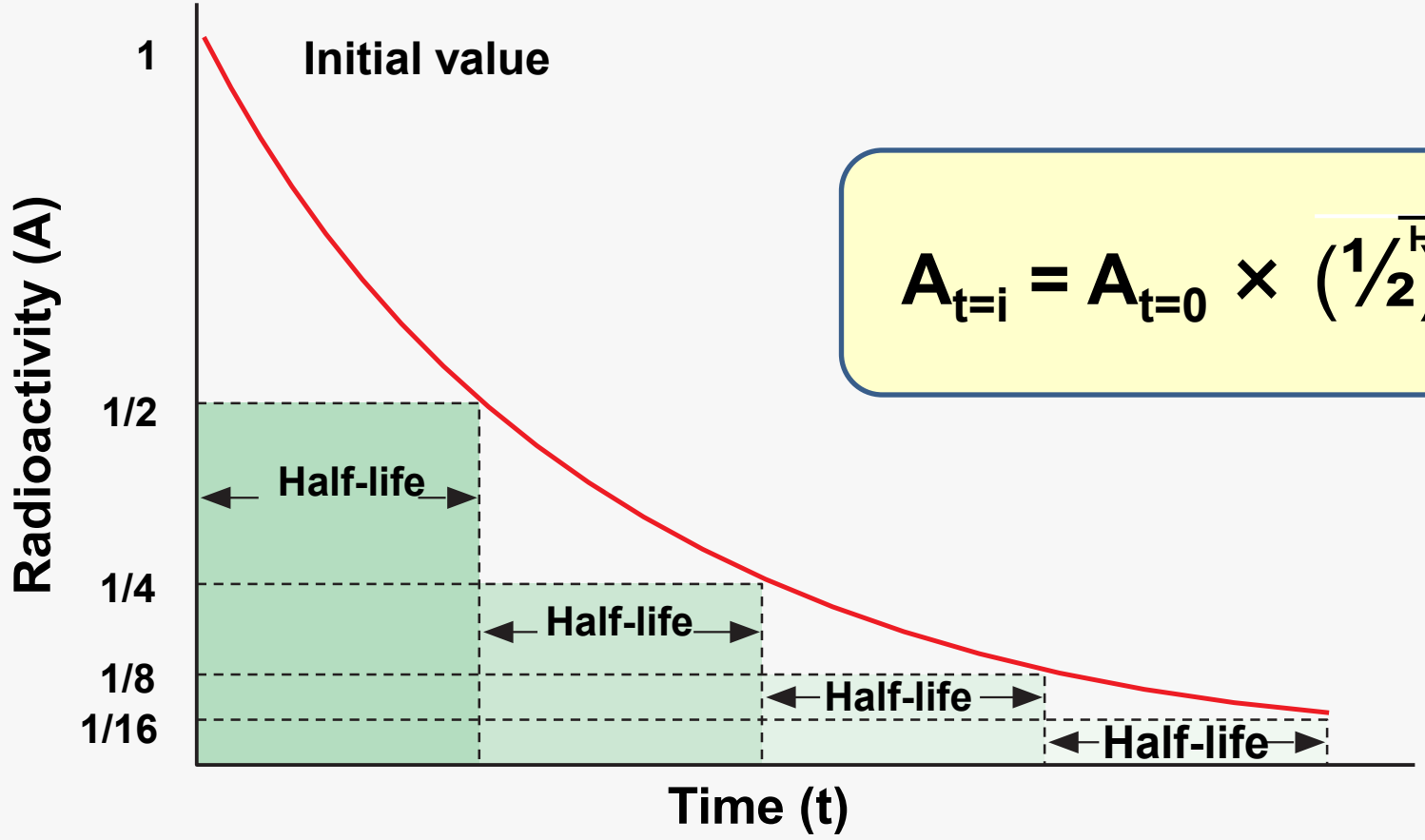
Unit to show the strength of radioactivity: becquerel (Bq)

Unit to show the degree of radiation effect: sievert (Sv)

Radioactive Decay and Half Life

Half-life

The time in which the amount of radioactivity is reduced by half of its initial value.

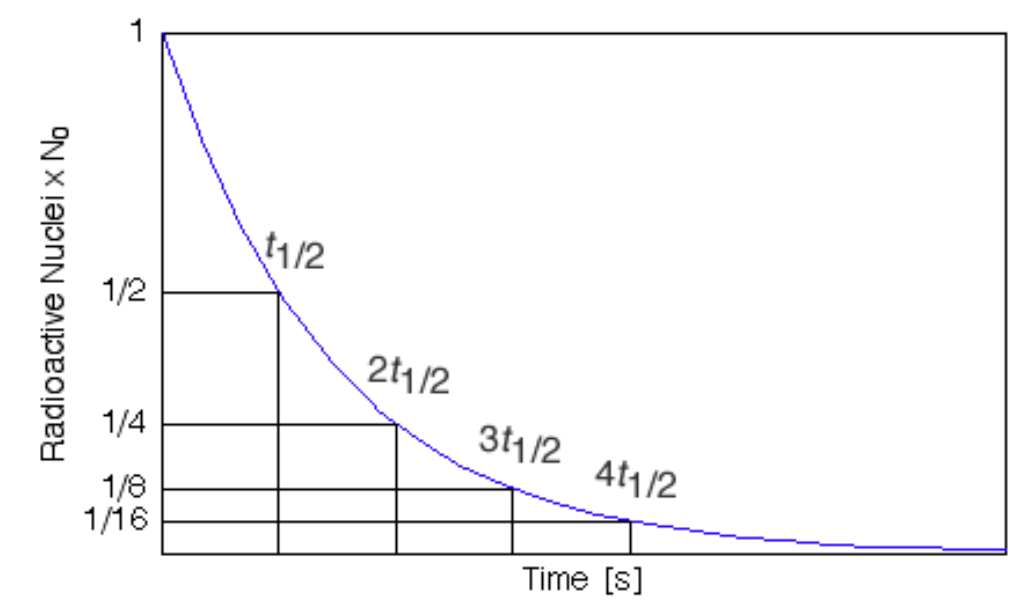


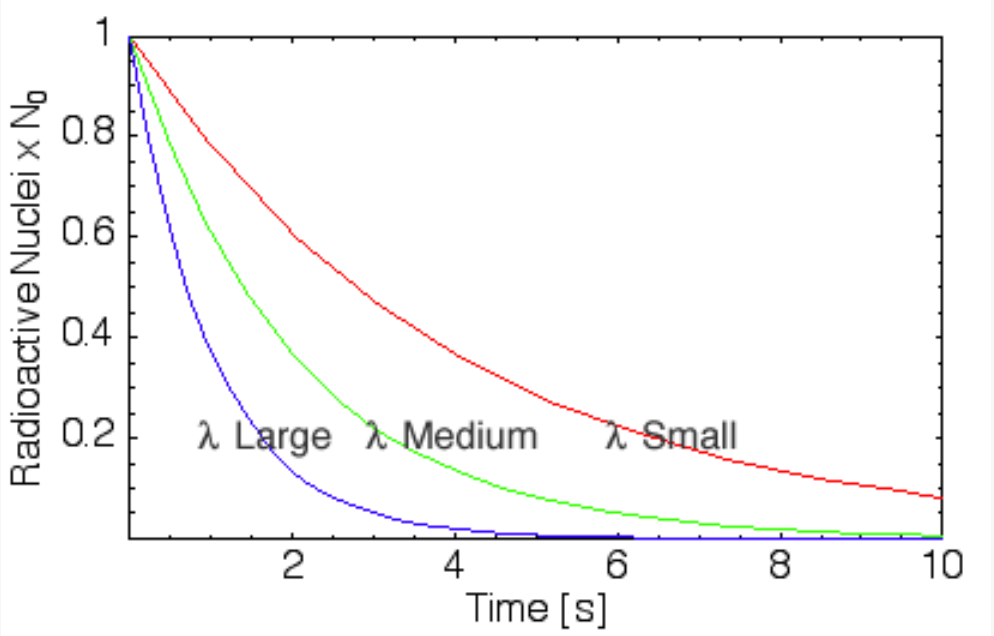
$$A_{t=i} = A_{t=0} \times \left(\frac{1}{2}\right)^{\frac{t}{\text{Half-life}}}$$

Radioactive Decay and Half Life

The activity, is measured in Becquerels [Bq]

1 Bq = 1 decay per second [dps]





	Half Life ($T_{1/2}$)	Decay Constant (λ)
^{134}Cs	2.1 y	1.07 x 10^{-8} s^{-1}
^{137}Cs	30.1 y	7.31 x 10^{-10} s^{-1}
^{131}I	8 d	1x10^{-6} s^{-1}

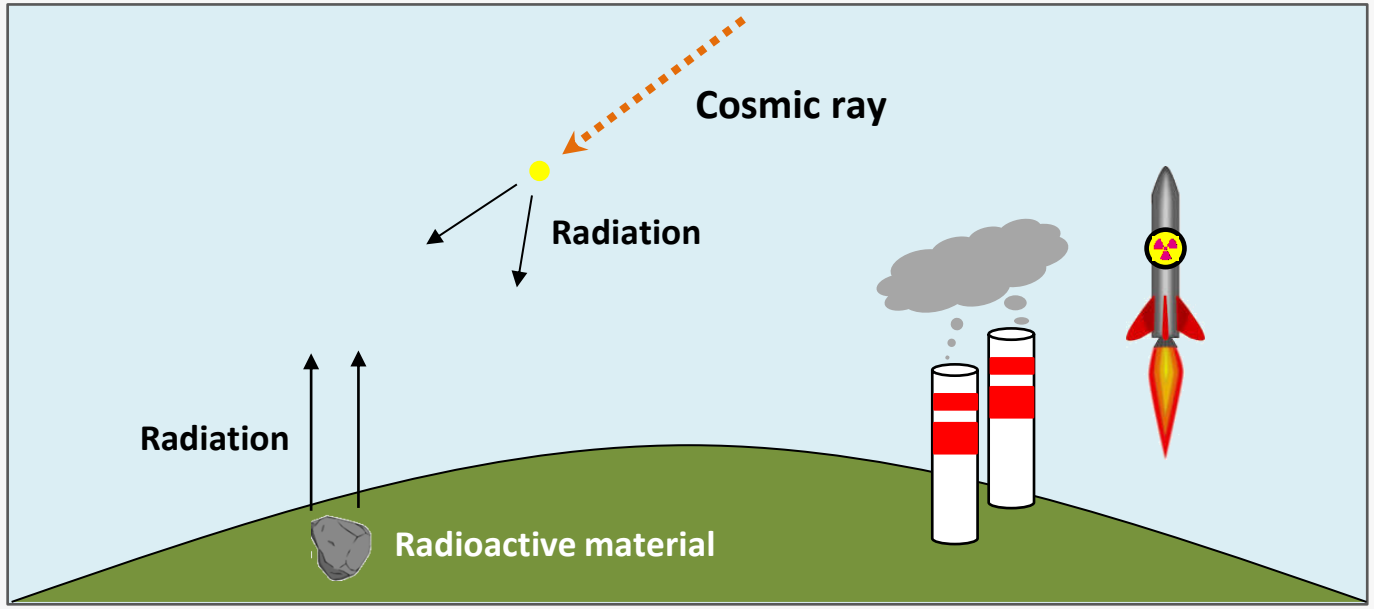
Types of Radiation Source

Natural Radiation:

- Cosmic rays
- Radioactive materials formed by the action of cosmic ray
- Radioactive materials contained in the ground

Man-made Radiation:

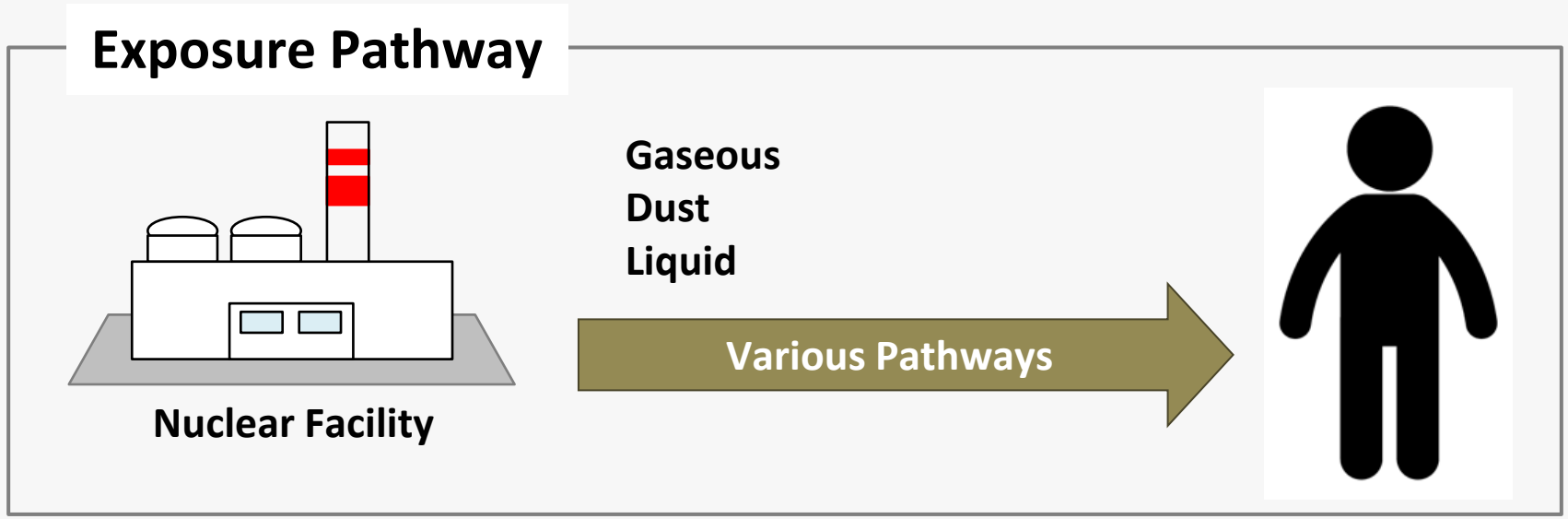
- Radioactive from atmospheric nuclear weapons tests
- Radioactive from nuclear facilities (NPPs, radioisotope facilities)



Masatsugu KAWASAKI
"Environmental Radiation Monitoring",
ITC 2014, JAEA

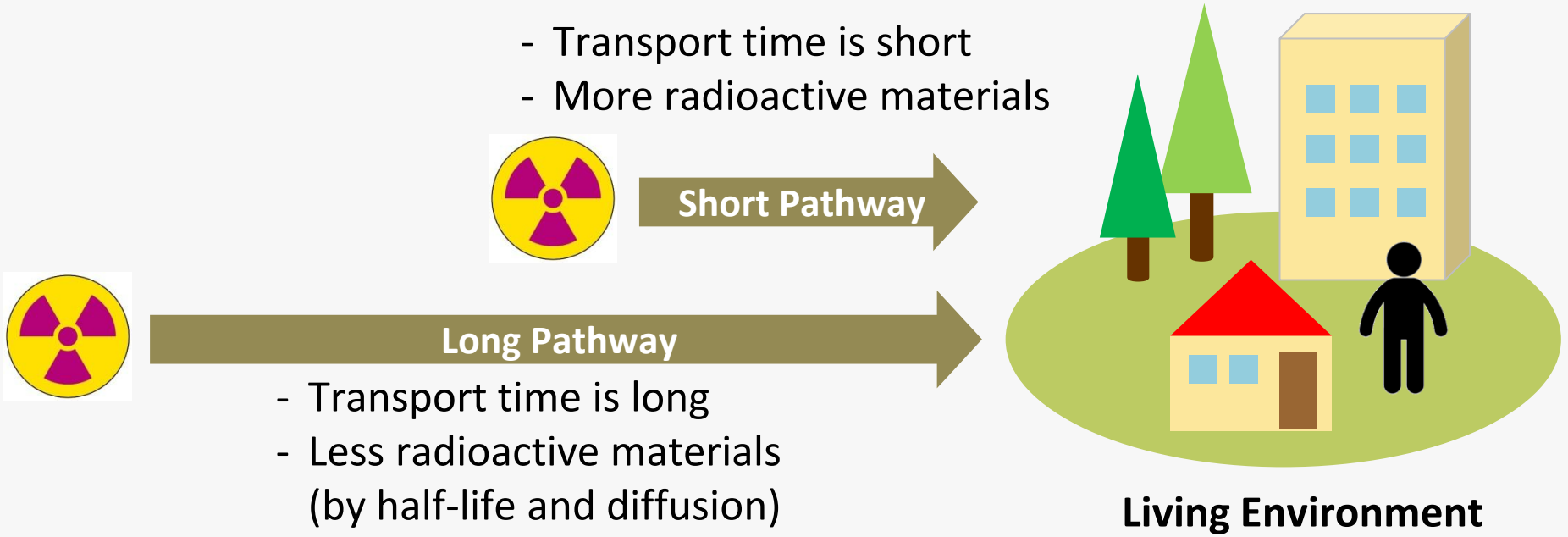
Exposure Pathways

- Pathway : Route of radionuclide transfer from source to recipient (human or biota)



Understanding the environmental behavior of radionuclides is important for effective radiation protection because it provides the scientific basis for evaluating, managing, and controlling radiation exposure to humans and other living organisms.

Features of Radioactive Materials on Pathways

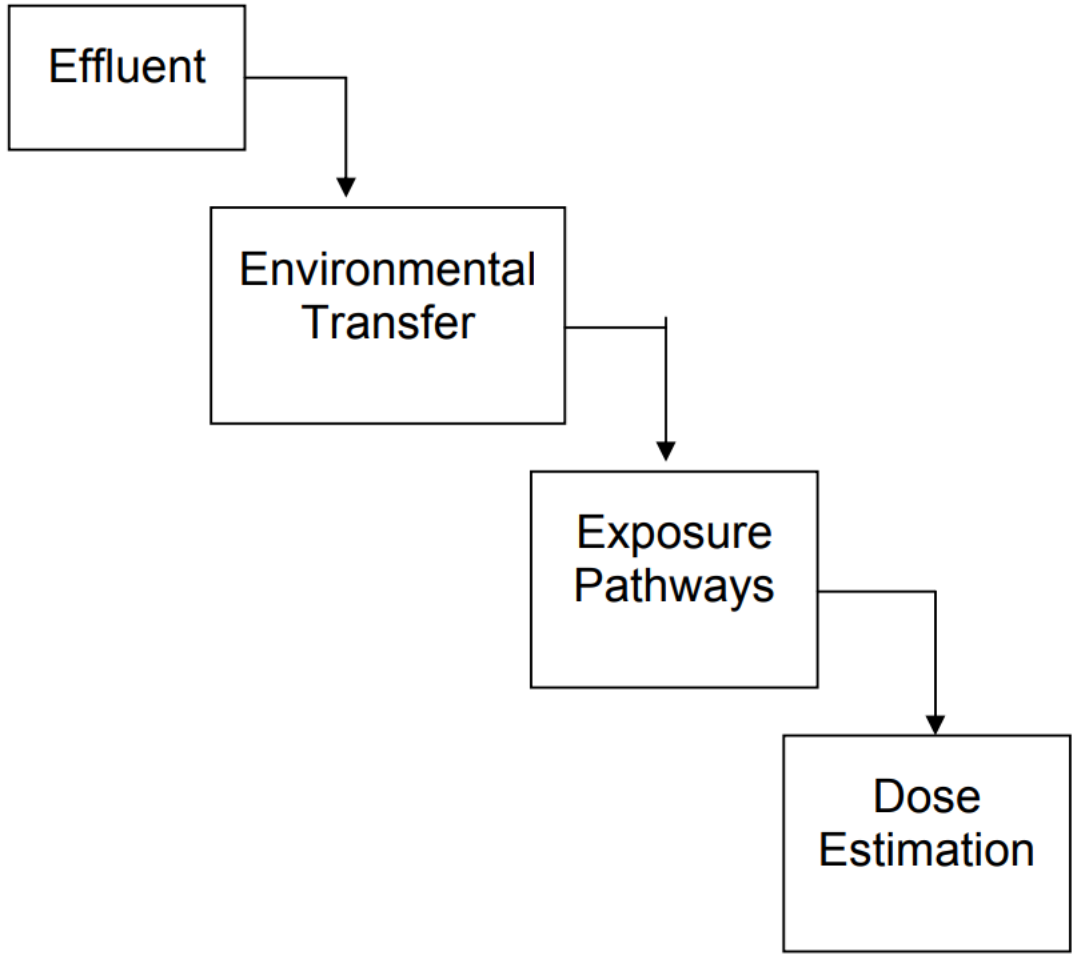


Short half-life nuclides:
External and internal exposure simply depends on their amounts to be released.
Long half-life nuclides:
The ground and oceans are greatly affected as long half-life nuclides are accumulated in the ground and water where foods and drinking water may get contaminated and leading to internal exposure.

Environmental Half-Life : Different from the physical half-life.It indicates the rate at which a radionuclide disappears from the environment due to a combination of decay, leaching, sorption, and biogeochemical processes.

Radiological Assessment

General Stages in the assessment of the radiological consequences of releases of radionuclides to the environment



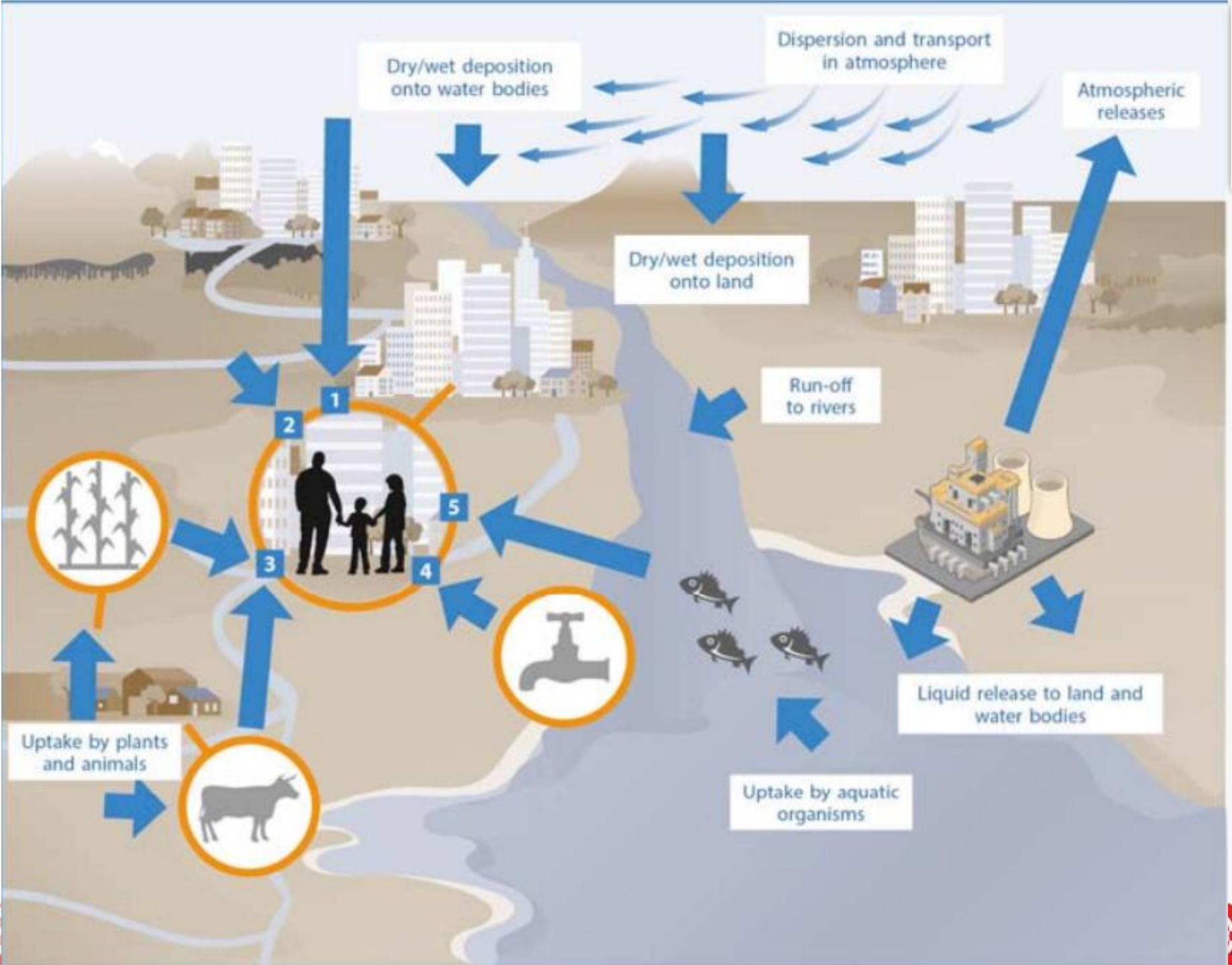
Critical Pathways:
Important pathways of exposure to person.

Critical Nuclides:
Important nuclides affect exposure of the general public.

Critical Groups:
Major groups of people exposed to critical nuclides.

Radiation Protection Division. (2009). The Methodology for Assessing the Radiological Consequences of Routine Releases of Radionuclides to the Environment Used in PC-CREAM 08

Exposure Pathways From Release of Radioactive Material to The Environment



1. Cloud immersion (external exposure, inhalation, and skin contamination)
2. External Exposure from deposits, re-suspension., and inhalation
3. Ingestion of crops, animal products, and terrestrial wildlife
4. Ingestion of drinking water
5. Ingestion of aquatic organism

UNSCEAR, 2013 report

Critical Nuclides

Type of facility	Radionuclides
Nuclear reactor facilities	**Gas** : radioactive noble gas, radioactive iodine **Liquid** : 3H, 51Cr, 54Mn, 59Fe, 58Co, 60Co, 89Sr, 90Sr, 131I, 134Cs, 137Cs
Reprocessing facilities	**Gas** : 3H, 14C, 60Co, 90Sr, 106Ru, 137Cs, 239Pu, 240Pu, radioactive noble gas, radioactive iodine **Liquid** : 3H, 60Co, 90Sr, 106Ru, 129I, 131I, 134Cs, 137Cs, 144Ce, 154Eu, 239Pu, 240Pu, 241Pu, 241Am, 244Cm
Fuel fabrication facilities	**Gas** : U **Liquid** : U
Radioactive waste facilities	**Gas** : 3H, 14C, 60Co, 59Ni, 63Ni, 90Sr, 94Nb, 99Tc, 129I, 137Cs, gross alpha **Liquid** : 3H, 14C, 60Co, 59Ni, 63Ni, 90Sr, 94Nb, 99Tc, 129I, 137Cs, gross alpha

Reference Level

- The **Environmental Radioactivity Reference Level (NBRL)** refers to a standard or **guideline value** that defines the **acceptable concentration or activity level of radionuclides** in different environmental media — under normal (**non-accidental**) conditions.
- It represents a **threshold below which the radiation exposure to humans and the environment is considered safe**, according to international and national radiation protection standards.
- Regulate discharges from nuclear facilities / industries to ensure they remain within permissible limits → **discharges limit**
- Nuclear Energy Regulatory Agency (BAPETEN) Chairman Regulation No. 7 year 2013 → no 7 year 2017 concerning Environmental Radioactivity Limit

Radionuclides Interaction with the Environment

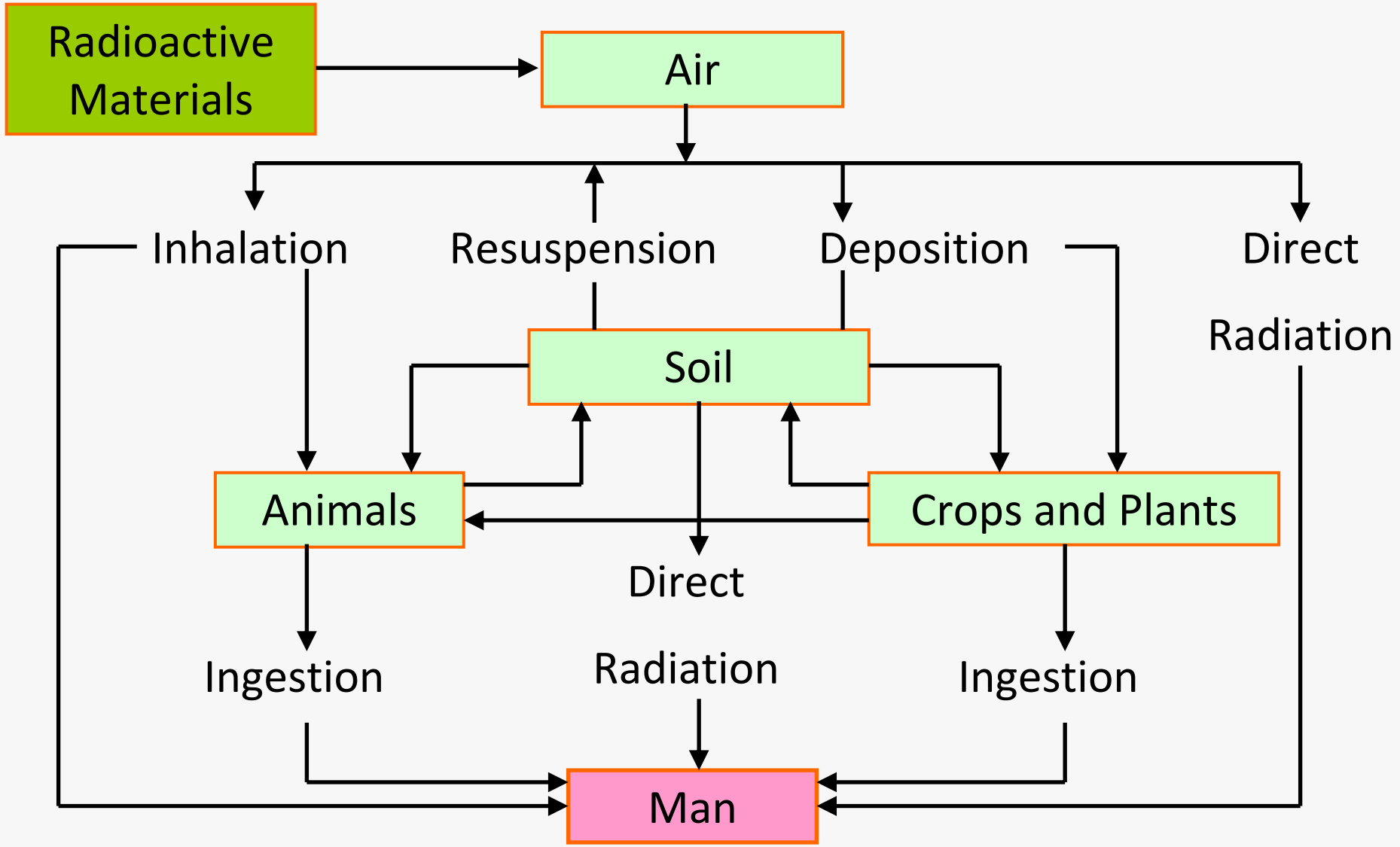
Main Environmental Compartment

- Radionuclides migrate among environmental compartments: **Atmosphere** (dispersion, deposition), **Soil/Sediment** (adsorption, ion exchange), **Water** (dissolution, precipitation), and **Biota** (bioaccumulation and food chain transfer)

- The interaction of radionuclides with the environment involves physical, chemical, and biological processes controlling how radionuclides move, transform, and accumulate within air, soil, water, and biota. Understanding these interactions helps predict radionuclide transport and assess radiation risks.

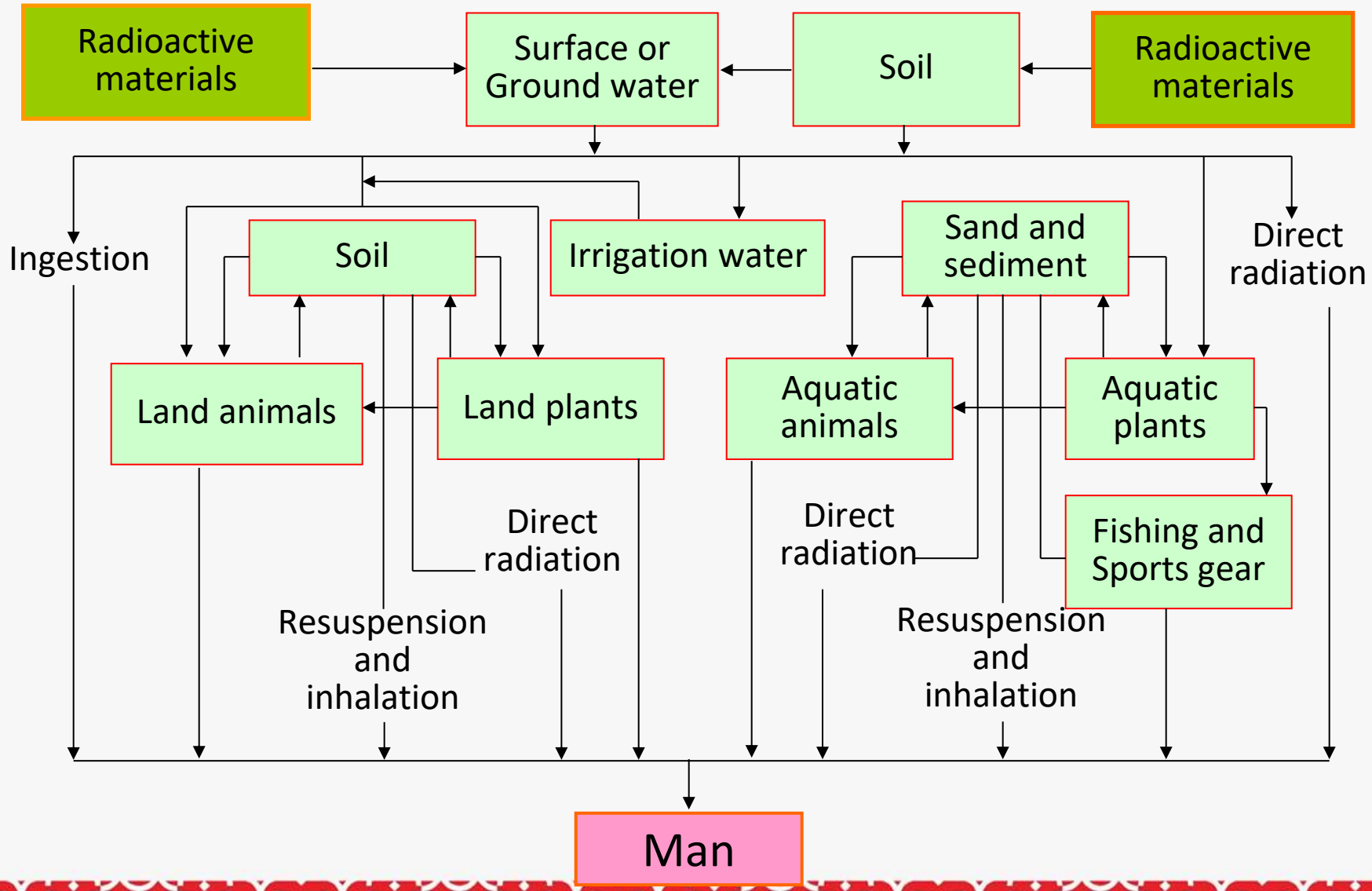
Compartment	Radionuclides	Main Mechanism
Atmosphere	^{3}H, ^{14}C, ^{131}I, ^{85}Kr	Atmospheric dispersion, dry deposition, wet deposition
Soil and Sediment	^{137}Cs, ^{90}Sr, ^{239}Pu	Adsorpsi, ion exchange, diffusion, leaching
Surface water and Ground Water	^{3}H, ^{99}Tc, ^{90}Sr	Dispersion, Precipitaion, hydrological transport
Biota (plants, animals, humans)	^{137}Cs, ^{90}Sr, ^{3}H	Bioaccumulation, biological transfer, biomagnification

Simplified Pathways of Radioactive Materials in Air



Masatsugu KAWASAKI "Environmental Radiation Monitoring", ITC 2014, JAEA

Simplified Pathways of Radioactive Materials in the Ground and Water



Mechanism and Interaction

Adsorption/desorption

- Radionuclides adhere to soil and mineral surfaces
- influenced by pH, mineral type, competing ions, and chemical form
- xample: Cs^+ strongly binds to clay minerals, reducing mobility.

Dissolution/precipitation

- Some radionuclides (e.g., tritium, strontium) dissolve easily
- while others (e.g., plutonium, americium) form insoluble compounds
- pH and redox conditions determine solubility behavior.

Ion exchange

- Charged radionuclides like Cs^+ and Sr^{2+} can replace other ions on mineral surfaces, affecting retention. Example: Cs^+ replaces K^+ in clay minerals, becoming tightly bound.

Complexation

- Radionuclides form stable complexes with inorganic ions (e.g., carbonate, nitrate) or organic compounds (e.g., humic acids)
- increasing mobility in organic-rich soils

Mechanism and Interaction

Migration and transport

- Once dissolved, radionuclides move via air, surface water, and groundwater.
- Transport depends on flow dynamics, adsorption, and speciation, key for predicting contamination spread

Biological uptake and transfer

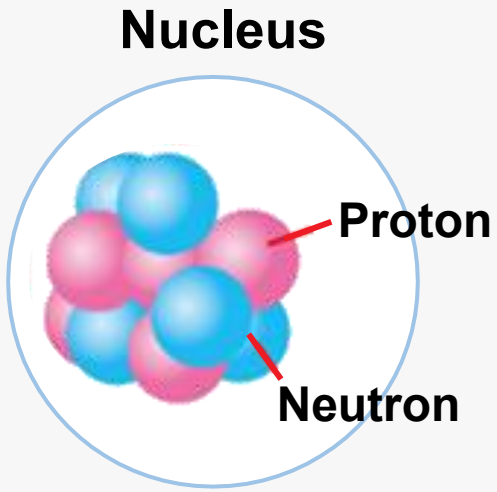
- Bioavailable radionuclides can be absorbed by plants and animals
- They enter the food chain and can undergo biomagnification (increased concentration at higher trophic levels)
- Example: Cs-137 acts like K, accumulating in the muscles of animals and humans.

Factors Influence Interaction

Factor	Influence
Physical and chemical forms of radionuclides	Determining solubility and reactivity
pH	Regulating the dissolution and redox state of radionuclides
Organic content	Can form complexes or increase mobility
Soil tekstur	Determining adsorption capacity
Rainfall and water flow	Affects transport and deposition
Types of organisms and biological metabolism	Determining bioaccumulation efficiency

Emission Type (Alpha, Beta, Gamma)

Indication of Isotopes



M : Symbol of atom
A : Mass Num (Z + n)
Z : Atomic Num (number of Protons)
N : A - Z

$${}^{A}_{Z}M$$

Name	*Atomic No (Z)*	*Mass No (A)*	*Example*
Isotope	Same	Different	Stable Isotope(^{1}H) Radioisotope (^{3}H)
Isobar	Different	Same	^{14}C and ^{14}N
Isomer	Same	Same	^{99}Tc and ^{99m}Tc

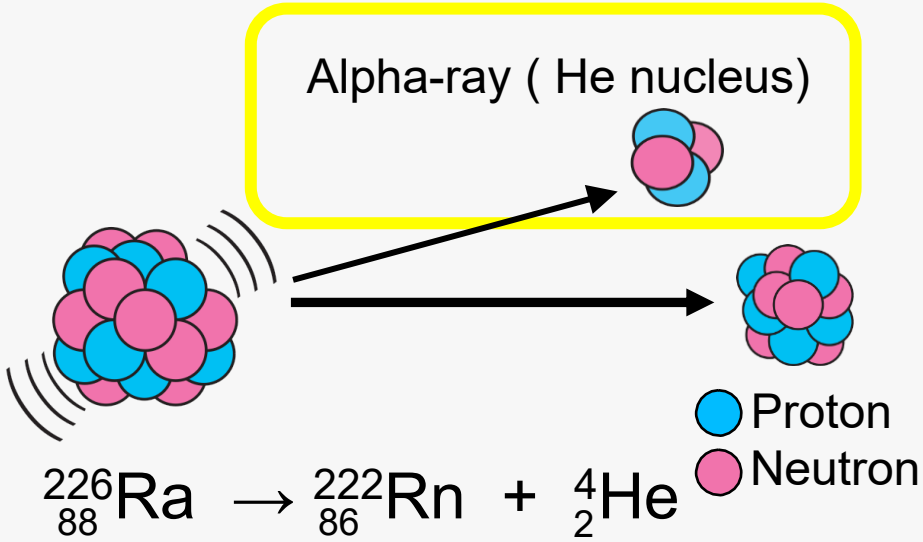
Alpha (α) Emission

Characteristics

- Alpha emission occurs when a nucleus **releases an alpha particle**, consisting of 2 protons and 2 neutrons (the same as a helium-4 nucleus)
- Written as $^{4}_{2}He$ or α
- Common in **heavy radionuclides**, such as uranium-238, radium-226, and plutonium-239.

General equation:

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



Radiation properties

- **Very low penetrating power** (can be stopped by paper or human skin)
- **Very high ionization power** (creates many ions along its path)
- Dangerous **if inhaled or ingested**, as it causes severe localized biological damage.

Example:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

Beta (β) Emission

There are two main types: **beta-minus (β⁻)** and **beta-plus (β⁺)**

1. Beta-minus (β⁻) decay

- Occurs when a neutron transforms into a proton, releasing an electron (β⁻) and an antineutrino
- Common in radionuclides with excess neutrons.

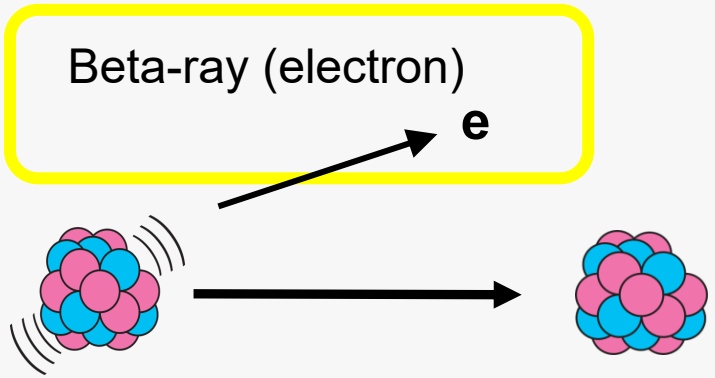
$$^{A}_{Z}X \rightarrow ^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e$$

Properties:

- Moderate penetrating power (can be stopped by a few millimeters of aluminum).
- Moderate ionization power.

Example:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + e^{-} + \bar{\nu}_e$$



$$^{32}_{15}P \rightarrow ^{32}_{16}S + e + \nu$$

2. Beta-plus (β⁺) decay

- Occurs when a proton transforms into a neutron, emitting a positron (β⁺) and a neutrino
- Common in radionuclides with excess protons.

$$^{A}_{Z}X \rightarrow ^{A}_{Z-1}Y + e^{+} + \nu_e$$

Example:

$$^{11}_{6}C \rightarrow ^{11}_{5}B + e^{+} + \nu_e$$

Gamma (γ) Emission

Characteristics

- Gamma emission is **high-energy electromagnetic radiation** emitted from a nucleus in an excited state as it moves to a more stable energy level
- There is **no change in the number of protons or neutrons**, only a **decrease in nuclear energy**.

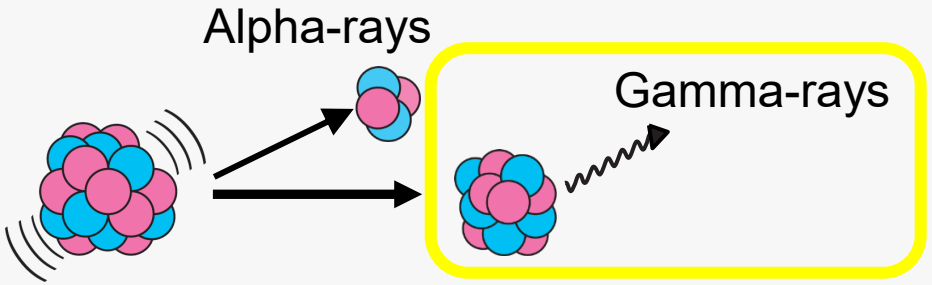
$$^{A}_{Z}X^{*} \rightarrow ^{A}_{Z}X + \gamma$$

Radiation properties

- **Very high penetrating power** (can pass through several centimeters of lead or meters of concrete)
- **Low ionization power** compared to alpha and beta
- Usually **accompanies alpha or beta decay.**

Example:

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + \beta^{-} + \gamma$$



Gamma-rays are waves with a shorter wavelength. They are released by alpha and beta decay.

Relationship Between Decay Mechanism and Environmental Behavior

Type of Decay	Physical Characteristics	Influence on Environmental Behavior
Alpha (α)	Large, positively charged particle; very short range (a few cm in air or μm in tissue)	• Cannot travel far in air or water • Dangerous mainly if inhaled or ingested • Often associated with particulate matter or sediments.
Beta (β)	Small, charged electron or positron; medium range	• Can move through water or soil • Beta emitters are often soluble (e.g., Sr-90, H-3) • Can enter food chains and affect organisms internally.
Gamma (γ)	High-energy electromagnetic radiation; no mass or charge	• Can penetrate deeply through air, soil, and tissue • Does not change the radionuclide's chemical form but defines external exposure range • Gamma emitters (e.g., Cs-137, Co-60) are easily detected in all media.

Effects of Decay Mechanism on Environmental Behavior

Mobility in Environmental Media

- Alpha-emitting radionuclides are usually less mobile
- Beta and gamma emitters are typically more mobile

Physical and Chemical Forms

- The decay process produces daughter nuclides with different chemical properties
- Example: U-238 → Th-234, where the product has new chemical reactivity affecting its distribution in soil or water.

Half-Life

- The decay mechanism is related to nuclear stability, resulting in different half-lives
- The half-life determines how long a radionuclide persists in the environment

Biological Hazard Potential

- Alpha radiation: highly dangerous if inhaled or ingested, but not externally
- Beta radiation: can penetrate thin skin layers, causing moderate external exposure
- Gamma radiation: dangerous both externally and internally due to high penetration power.

Monitoring and Remediation

- The decay type determines the detection method (alpha, beta, or gamma detectors)
- It also affects waste management or remediation strategies (e.g., alpha waste needs strong containment, gamma needs lead shielding).

Radionuclide	Decay Type	Environmental Behavior	Main Impact
U-238	Alpha	Poorly soluble, adheres to sediments	Hazardous when inhaled as dust
Sr-90	Beta	Chemically similar to calcium, absorbed by plants and bones	Bioaccumulates in food chains
Cs-137	Beta & Gamma	Highly soluble, mobile in water	Causes widespread external exposure
I-131	Beta & Gamma	Volatile, easily enters food chains	Concentrates in the human thyroid gland

Influence of Physical and Chemical Forms on Dispersion Potential

Physical Form of Radionuclides

Physical Form	Example	Characteristics	Impact on Distribution
Gass	Tritium gass (HT), Iodine-131, Krypton-85	Can spread quickly in the atmosphere, easy to inhale	High mobility, easy to spread long distances
Aerosol	Cs-137, Sr-90 (in radioactive dust)	Sticks to dust particles or water vapor	Can be inhaled, deposited in soil and water
Solid	PuO_2, UO_2	Stable, not easily dissolved	Low mobility, but dangerous if inhaled
Aqueous	HTO (tritiated water), Cs-137, Sr-90 in soluble ionic form (Cs^+, Sr^{2+}).	Easily move in groundwater or rivers	High mobility in water systems
Adsorbed on particles	Cs-137 in clay minerals	Absorbed on soil particles	Mobility depends on surface chemical interactions

Physical Form of Radionuclides

- Particulate radionuclides (e.g., uranium oxide particles) tend to deposit close to their release site due to gravitational settling. They may adhere to soil, sediment, or biological surfaces
- Gaseous radionuclides (e.g., radon, tritium as HTO vapor) disperse widely in the atmosphere, increasing the scale of exposure. Their mobility makes them harder to control and predict
- Volatile radionuclides such as iodine-131 and tritium (HTO) can vaporize and disperse in the atmosphere. This property is especially important in nuclear accidents
- Volatile species may condense on aerosols, leading to deposition on surfaces and entry into the food chain.

Chemical Form of Radionuclides

Physical Form	Example	Characteristics	Impact on Distribution
Free Ion	Cs^{+}, Sr^{2+}	Very soluble in water	Easily absorbed by plant roots and aquatic organisms
Oksida / Hidroksida	PuO_2, $Am(OH)_3$	Generally insoluble	Fixed in sediment or soil, low mobility
Anorganic complex	UO_2^{2+}, TcO_4^{-}	Soluble in water	Transfer long distances through water currents
Organic complex	Kompleks Pu-humic acid	Stable in organic environments	Increase mobility in organic soil
Organically Bound Form (OBT)	Tritiated organic compounds	Bound in biological networks	Long-lasting in organisms and food chains

Chemical Form of Radionuclides

- Soluble radionuclides (e.g., tritium, cesium-137) dissolve easily in water, facilitating long-range transport in rivers, lakes, and groundwater. They are also more likely to be taken up by plants and aquatic organisms
- Insoluble radionuclides (e.g., plutonium oxides) tend to settle in sediments or remain bound to particles, limiting mobility but posing long-term risks as they accumulate
- Radionuclides can exist in multiple oxidation states, influencing their solubility and mobility. For example, uranium can exist as U(IV) (less soluble, tends to precipitate) or U(VI) (more soluble, migrates with groundwater)
- Plutonium exhibits complex chemistry, forming colloids that increase its transport potential

Implications for Environmental Assessment

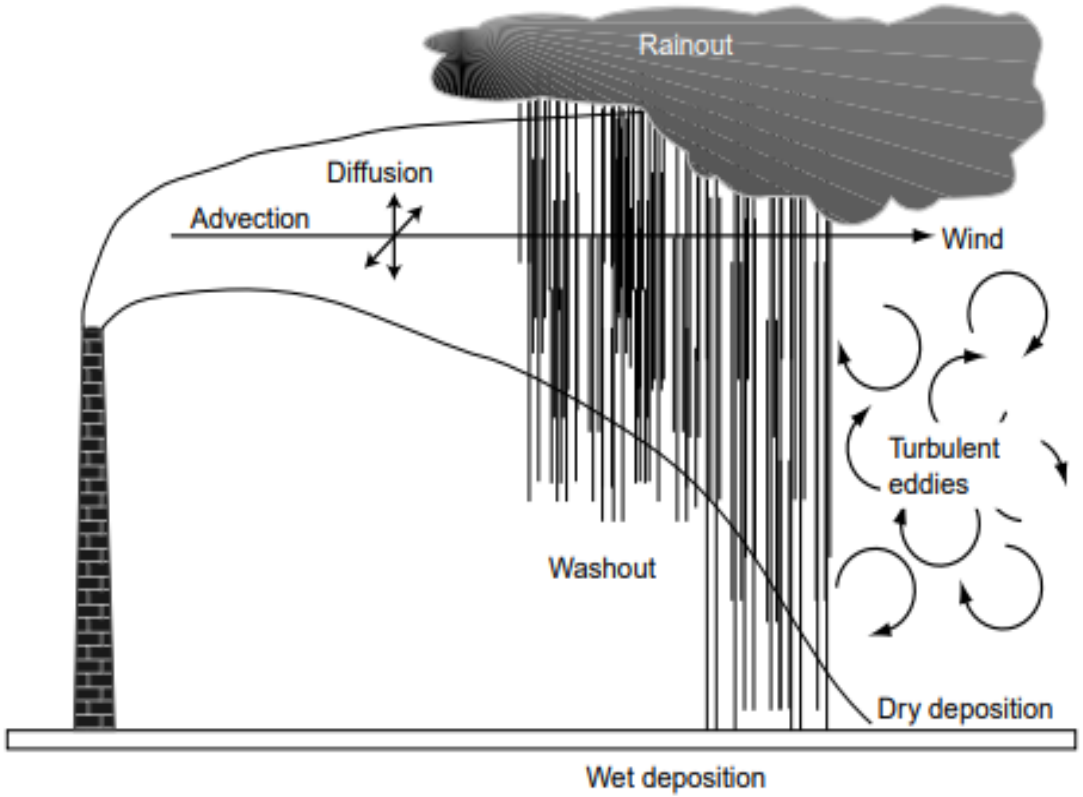
The dispersion of radionuclides in the environment is strongly influenced by their physical and chemical forms. Factors such as solubility, volatility, particle size, oxidation state, and chemical bonding determine how radionuclides move through air, water, soil, and biological systems. Understanding these properties is essential for predicting environmental behavior and assessing radiation risks.

- Understanding the physical and chemical forms of radionuclides allows more accurate predictions of their transport and fate
- It informs remediation strategies, such as choosing barriers or sorbents to immobilize radionuclides
- Risk assessments must consider both immediate mobility and long-term transformations of radionuclides in the environment.

Radionuclide Behavior in The Atmosphere

Atmospheric Processes Affecting Radionuclide Behavior

Once released into the air, radionuclides can exist in **gaseous form**, **attached to aerosol particles**, or **as part of fallout materials**.
Their **behavior, residence time, and distribution** depend on the physical and chemical properties of the radionuclides and on atmospheric conditions (e.g., wind, temperature, humidity, and precipitation).



1. Dispersion and Transport

Once released, radionuclides are transported by **wind** and **turbulent mixing**.
Dispersion depends on:

- Wind speed and direction,
- Atmospheric stability,
- Height of release (e.g., ground level vs. stack or explosion height).

Atmospheric Processes Affecting Radionuclide Behavior

2. Chemical Transformation

Some radionuclides undergo **chemical reactions** in the atmosphere:
Iodine-131 can exist in molecular form (I_2), organic iodides (CH_3I), or as aerosols.
Tritium (^3H) can form **tritiated water vapor (HTO)**, which behaves like normal water vapor and quickly exchanges with atmospheric moisture.
These transformations affect their residence time and deposition pathways

3. Aerosol Attachment

Many radionuclides quickly attach to **atmospheric aerosols** (dust, smoke, sea salt, or industrial particles).
This attachment influences:

- The size of the particle,
- Its ability to remain airborne, and
- Its removal rate via precipitation or dry settling.

Fine aerosols (<1 μm) can stay airborne for days to weeks, allowing for long-range transport.

Atmospheric Processes Affecting Radionuclide Behavior

4. Deposition Processes

Atmospheric radionuclides are removed primarily by **two mechanisms**:

- **Dry deposition:**
  Direct settling or impaction of particles or gases onto surfaces (soil, vegetation, buildings). Influenced by particle size, wind speed, and surface roughness. Dominant near emission sources.
- **Wet deposition (scavenging):**
  Removal by rain, snow, or fog through **in-cloud** or **below-cloud** scavenging. Very efficient for soluble or aerosol-attached radionuclides. Causes rapid decrease in air concentration after rainfall events.

5. Resuspension

Previously deposited radionuclides can be **resuspended** into the air by:
Wind erosion of contaminated soil or dust,
Agricultural activities,
Forest fires or volcanic events.
Resuspension contributes to **chronic low-level exposure** long after the initial release.

Atmospheric Processes Affecting Radionuclide Behavior

Atmospheric Residence Time
The time radionuclides remain in the atmosphere varies widely:
- **Gaseous forms (e.g., ^{14}C, Rn)**: days to weeks.
- **Fine aerosols (e.g., Cs-137)**: days to months.
- **Large particles**: a few hours to days (settle quickly).

Residence time affects **global circulation and fallout patterns**.

- The behavior of radionuclides in the atmosphere is governed by **complex interactions** between physical, chemical, and meteorological processes
- Atmospheric half-life and volatility strongly influence persistence and spread
- Atmosphere acts as the **main pathway** for dispersion after releases
- Deposition processes determine **radiation exposure and contamination distribution**
- Continuous monitoring and modeling are vital for **emergency response and radiation protection**.

Radionuclide Behavior in Surface Water and Ground Water

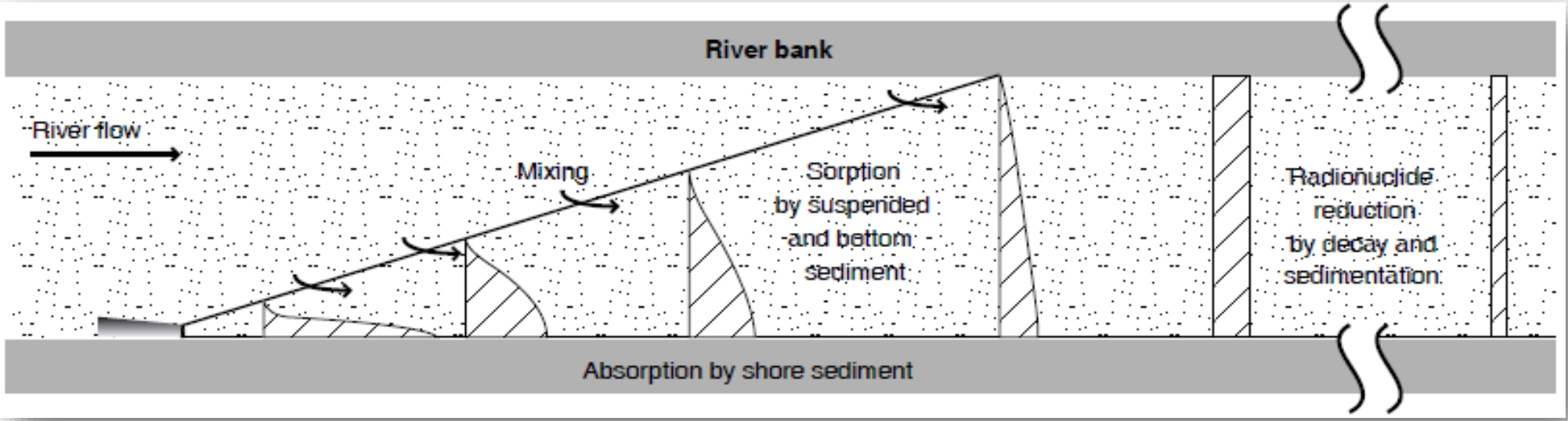
Behavior in Surface Water

Radionuclides can enter aquatic systems (both surface and groundwater) through various pathways — such as discharges from nuclear facilities, fallout from atmospheric testing, or natural leaching from geological formations containing uranium and thorium. Understanding their behavior in these water systems is crucial for assessing potential human and ecological exposure.

Antropogenic Radionuclide

- Conservative : It is very soluble in seawater, so its distribution is greatly influenced by physical processes in the form of advection and diffusion. Ex : ^{137}Cs, ^{90}Sr, ^{14}C, ^{129}I dan ^{3}H
- Particle reactive : It is easier to disappear from the sea due to its affinity for the surface of natural particles which causes this radionuclide to sink to the seabed and enter the sediment. Ex : ^{239}Pu, ^{240}Pu, ^{106}Ru dan ^{144}Ce

Radionuclide Transport in Surface Water

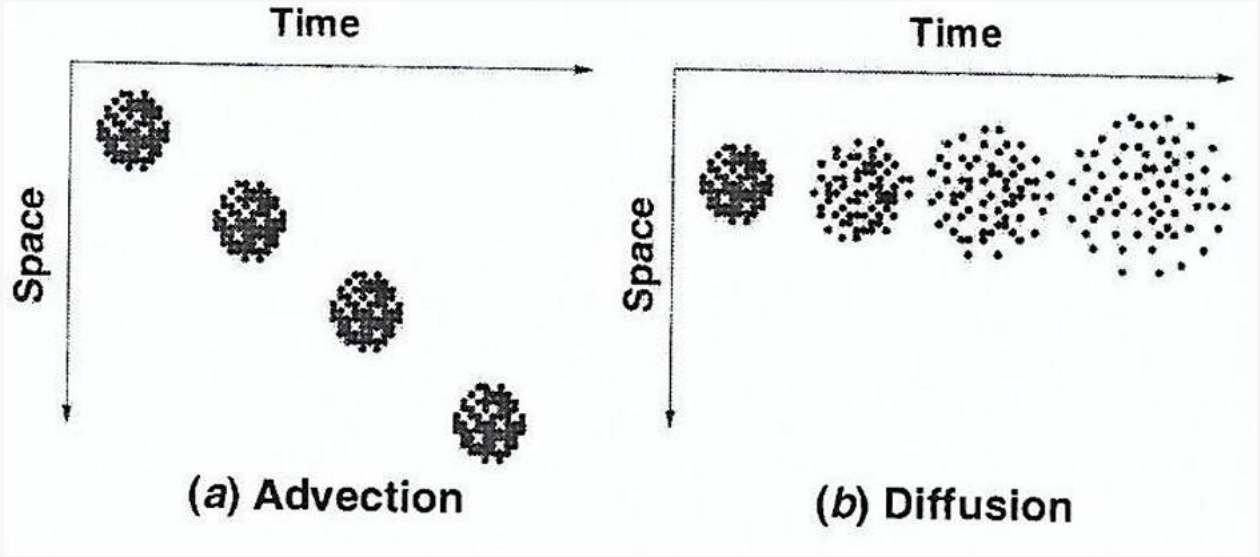


Radionuclides discharged into surface waters are subject to a series of physical and chemical processes that affect their transport from the source point :

- **Flow processes**, such as downcurrent transport (advection) and mixing processes (turbulent dispersion)
- **Sediment processes**, such as adsorption/desorption on suspended, shore/beach and bottom sediments, and downcurrent transport, deposition and resuspension of sediment, which adsorbs radionuclides
- **Other processes**, including radionuclide decay and other mechanisms that will reduce concentrations in water, such as radionuclide volatilization

Radionuclide Transport in Surface Water

- Advection : the process of moving substances as a result of a flow that is unidirectional and does not change the identity of the substance that is flowing/moving
- Diffusion : mass movement due to random motion of water molecules or due to mixing motion



Processes Affecting Radionuclides in Surface Water

1. Dissolution and Speciation
- Radionuclides dissolve in water and exist in different chemical forms (ionic, colloidal, or particulate)
- Speciation determines their mobility and bioavailability
- Example: Cesium-137 (Cs^+) behaves as a cation and is easily adsorbed by clay particles.

2. Sorption and Desorption
- Radionuclides may attach to suspended sediments or organic matter (sorption)
- Changes in pH, salinity, or redox potential can cause desorption, releasing radionuclides back into the water column

3. Sedimentation and Resuspension
- Sediments act as a **sink** for radionuclides
- Under disturbance (e.g., floods, currents), radionuclides can be **resuspended**, reintroducing contamination to the water column

4. Biological Uptake and Bioaccumulation
- Aquatic plants and organisms absorb radionuclides
- Bioaccumulation occurs along the **food chain**, potentially reaching fish consumed by humans
- Example: Strontium-90 behaves like calcium and can accumulate in fish bones and shells.

Transport in Groundwater

Groundwater is a key pathway for radionuclide migration from waste disposal sites or contaminated soils. Its movement is generally **slower but more persistent** compared to surface water

Sources of Radionuclide Pollution in Groundwater :

- Rainwater infiltration, which dissolves radionuclides from the soil or radioactive
- Waste.Seepage (leaks) from underground radioactive waste storage sites
- Natural dissolution of rocks containing radioactive elements, such as uranium (U), thorium (Th), and radium (Ra)
- Industrial accidents or releases, such as from nuclear facilities or radioactive material mining.

Mechanisms Controlling Behavior in Groundwater

Groundwater is a key pathway for radionuclide migration from waste disposal sites or contaminated soils.
Its movement is generally **slower but more persistent** compared to surface water

Mechanisms Controlling Behavior in Groundwater

1. **Advection and Dispersion**
   - Radionuclides are transported along groundwater flow paths (advection)
   - Dispersion spreads the contamination plume laterally and vertically.
2. **Sorption on Aquifer Materials**
   - Radionuclides are transported along groundwater flow paths (advection)
   - Dispersion spreads the contamination plume laterally and vertically.
3. **Precipitation and Co-precipitation**
   - Under certain conditions, radionuclides form insoluble compounds (e.g., uranium oxides, radium sulfate) that precipitate out of solution
4. **Colloid-Facilitated Transport**
   - Some radionuclides attach to microscopic colloids (nanoparticles), allowing them to move further than expected through porous media
5. **Decay and In-growth**
   - Radioactive decay naturally reduces radionuclide concentration, but daughter products may also be radioactive (e.g., Uranium-238 → Radium-226 → Radon-222).

Factors Influencing Radionuclide Mobility

Factor	Influence
pH	Controls ionization and sorption; acidic conditions increase solubility.
Redox Potential (Eh)	Determines oxidation state; e.g., U(IV) is less soluble than U(VI).
Temperature	Affects solubility and reaction kinetics.
Mineralogical Composition	Clay and iron oxides enhance sorption capacity.
Organic Matter	Complexes radionuclides, sometimes increasing mobility.

Summary

- **Surface Water:** Rapid transport, but dilution and dispersion often reduce concentration; however, contamination of aquatic food webs can persist
- **Groundwater:** Slow movement but long-term contamination risk; difficult and costly to remediate once radionuclides infiltrate aquifers
- **Human Exposure Pathways:** Drinking water, irrigation, fish consumption, and use of contaminated groundwater
- Soluble radionuclides (tritium, cesium-137) disperse widely in rivers, lakes, and oceans
- Transport depends on water currents, mixing, and dilution
- Radionuclides may adsorb onto suspended sediments, influencing deposition in aquatic systems
- Bioavailability in aquatic food chains is strongly linked to chemical form.

Case Example: Strontium-90 in Rivers
Sr-90, produced by nuclear fallout, behaves chemically like calcium. It dissolves in water and is transported downstream, eventually entering aquatic organisms. Its integration into bones poses long-term health hazards for both animals and humans.

Radionuclide Behavior in Soil and Sediment

Main Processes Affecting Radionuclide Behavior in Soil (1/3)

- Soil plays a critical role in controlling the fate and transport of radionuclides in the environment. Soil determines whether radionuclides remain fixed, migrate into groundwater, or become available for uptake by plants and entry into the food chain
- Radionuclides deposited on soil may remain at the surface or migrate downwards depending on solubility and rainfall

1. Deposition and Retention

When radionuclides are deposited on the soil surface (via air deposition or water infiltration), they can adhere to soil particles through physical and chemical bonding. Retention depends on **soil texture**, **mineral composition**, and **organic matter content**.

Main Processes Affecting Radionuclide Behavior in Soil (2/3)

2. Adsorption and Desorption

- **Adsorption** occurs when radionuclide ions attach to the surfaces of clay minerals, oxides (Fe, Al, Mn), or organic matter. This process **reduces mobility** and **prevents leaching** into groundwater.
- **Desorption** happens when changes in **pH**, **ionic strength**, or **redox potential** release radionuclides back into the soil water phase, making them mobile again.
  Example: Cesium-137 (Cs^{+}) strongly adsorbs onto clay minerals (especially illite), while strontium-90 (Sr^{2+}) is more weakly bound and more mobile

3. Ion Exchange

Soil colloids (especially clays) act as ion exchangers.
Radionuclides can replace other cations (Ca^{2+}, K^{+}, Na^{+}) on the exchange sites.
The strength of exchange depends on the radionuclide's **charge density and hydration energy**.

4. Complexation with Organic Matter

Organic materials in soil, such as humic and fulvic acids, can form **complexes** with radionuclides.
These complexes may:

- Enhance mobility (if soluble), or
- Immobilize radionuclides (if strongly bound to humic substances).

Example: Uranium can form soluble uranyl-carbonate complexes in the presence of organic ligands and high carbonate concentrations

Main Processes Affecting Radionuclide Behavior in Soil (3/3)

5. Precipitation and Co-precipitation

Under certain chemical conditions, radionuclides form **insoluble compounds** and precipitate out of solution.

Example:

- Uranium can precipitate as $UO_2(s)$ under reducing conditions.
- Radium can co-precipitate with barium or sulfate minerals ($BaSO_4$, $RaSO_4$).

6. Redox Reactions

Redox potential (Eh) governs the **oxidation state** of radionuclides, affecting solubility and mobility:

- Reduced forms (e.g., U(IV), Tc(IV), Pu(IV)) → less soluble, less mobile
- Oxidized forms (e.g., U(VI), Tc(VII), Pu(VI)) → more soluble, more mobile.

7. Diffusion and Leaching

Infiltrating rainwater can transport soluble radionuclides downward through the soil profile, leading to **vertical migration** and potential contamination of groundwater

8. Biological Uptake

Soil microorganisms, fungi, and plants can uptake radionuclides, altering their chemical form or redistributing them within the soil.

- For instance, plants may absorb strontium-90 as it mimics calcium or cesium-137 as it mimics potassium
- The uptake creates a **transfer pathway to the food chain**.

Factors Controlling Radionuclide Mobility in Soil

Factor	Effect on Behavior
Soil pH	Low pH increases solubility and mobility.
Cation Exchange Capacity (CEC)	Higher CEC = stronger radionuclide adsorption.
Organic Matter	Can bind or mobilize radionuclides.
Redox Conditions	Control oxidation state and solubility.
Clay Content	Clays like illite and montmorillonite enhance adsorption.
Moisture and Temperature	Affect chemical reactions and microbial activity.

Processes Affecting Radionuclide Behavior in Sediment (1/4)

- When radionuclides enter water systems (through atmospheric fallout, industrial discharge, or natural processes), they often attach to suspended particles and eventually settle to the bottom, forming contaminated sediment layers.
- Sediments play a crucial role in controlling the transport, accumulation, and long-term fate of radionuclides in aquatic environments
- Sediments act as long-term reservoirs, slowly releasing radionuclides back into water under changing chemical conditions

1. Sedimentation and Particle Association

Most radionuclides in aquatic systems are **particle-reactive**, meaning they preferentially bind to **suspended solids, organic matter, and minerals** rather than staying dissolved in water.
These particles eventually **settle** through sedimentation, transferring radionuclides from the water column to the bottom sediments.
For example:

- **Cesium-137 (Cs-137)** tends to bind strongly to clay minerals
- **Plutonium (Pu)** and **Americium (Am)** attach to fine-grained particles and organic matter.

Processes Affecting Radionuclide Behavior in Sediment (2/4)

2. Adsorption and Desorption

- **Adsorption:** The attachment of radionuclides onto sediment surfaces (especially clay minerals, oxides of Fe, Mn, and Al, and organic matter).
- **Desorption:** The reverse process, where radionuclides are released back into the water phase.

Desorption can be triggered by:

- Changes in **pH** or **redox conditions**
- Increased **ionic strength** (salinity)
- Complexation with organic ligands.

Implication: Sediments can act as a *temporary storage* that releases radionuclides under disturbed conditions (e.g., dredging or floods).

Processes Affecting Radionuclide Behavior in Sediment (3/4)

3. Diffusion and Pore Water Exchange

Radionuclides can **diffuse** between solid sediment particles and the **interstitial water (pore water)** within sediments.

This exchange determines how radionuclides move between the **sediment and overlying water**, influencing long-term contamination levels

4. Redox Reactions

Redox conditions (oxidizing or reducing environments) in sediments significantly affect the **chemical speciation** and **mobility** of radionuclides.

- Under **oxidizing conditions**, many radionuclides (e.g., U(VI), Tc(VII)) remain soluble and mobile.
- Under **reducing conditions**, they can precipitate as insoluble compounds (e.g., UO_2, TcO_2), becoming immobile.

Example: Uranium can transform from soluble U(VI) to insoluble U(IV) in anoxic sediments.

Processes Affecting Radionuclide Behavior in Sediment (4/4)

5. Complexation and Colloidal Transport

Natural organic matter and colloidal particles can bind radionuclides, forming **mobile complexes** that can migrate through sediments or resuspend into the water column. This process increases radionuclide mobility and may lead to **recontamination of surface waters**.

6. Bioturbation and Resuspension

Biological activities (e.g., burrowing organisms, microbial metabolism) can disturb sediment layers, redistributing radionuclides.

Similarly, **physical disturbances** (storms, currents, dredging) can **resuspend** contaminated sediments back into the water column, **reactivating previously settled radionuclides**.

Factors Influencing Radionuclide Mobility in Sediment

Factor	Influence
Grain size	Fine sediments (silt, clay) have higher adsorption capacity.
Organic matter content	Enhances radionuclide binding or complexation.
pH	Low pH increases desorption and solubility.
Redox potential (Eh)	Controls oxidation state and solubility.
Sediment composition	Fe/Mn oxides act as scavengers for radionuclides.
Microbial activity	Can alter redox conditions and radionuclide speciation.

Distribution Coefficient

- When sediment interacts with radionuclides dissolved in water, the concentration of the radionuclides in the dissolved phase may be decreased owing to radionuclide adsorption on to sediment particles. Consequently, the concentration of radionuclides on suspended sediment and the banks and bed of the water body will be increased owing to adsorption and particle settling.
- The distribution coefficient Kd (L/kg) is used to express the exchange of radionuclides between the dissolved and sediment sorbed phases and is defined for a given radionuclide as

$$Kd = \frac{konsentrasi\ radionuklida\ pada\ sedimenper\ satuan\ berat\ sedimen\ \left(\frac{Bq}{kg}\right)}{konsentrasi\ radionuklida\ terlarutper\ satuan\ volume\ air\ \left(\frac{Bq}{L}\right)}$$

Transfer into Biota and Food Chain

Pathways of Radionuclide into Biota

Environmental Compartment	Example of Uptake Pathway	Typical Radionuclides
Atmosphere → Plants	Deposition on leaves followed by foliar absorption	I-131, Cs-137
Soil → Plants (Root Uptake)	Root absorption from soil solution	Sr-90, Cs-137, U, Ra-226
Water → Aquatic Biota	Direct uptake from water or food	H-3, Cs-137, Co-60
Sediment → Bottom Dwellers	Ingestion or diffusion through tissues	Pu, Am, Ra
Biota → Higher Trophic Levels	Consumption of contaminated prey or vegetation	Cs-137, Sr-90, Pu isotopes

Mechanisms of Radionuclide Uptake

- **Direct Absorption**

  Organisms can absorb radionuclides directly from their environment through:
  - **Roots** (in plants),
  - **Gills or skin** (in fish and invertebrates),
  - **Inhalation or ingestion** (in animals and humans).

- **Indirect (Trophic) Transfer**

  When one organism consumes another containing radionuclides, **transfer through the food chain** occurs.
  This leads to **bioaccumulation** (build-up within an organism) and **biomagnification** (increase of concentration along trophic levels).

Bioaccumulation Factor

The transfer of radionuclides from water, through various trophic levels of aquatic life, to those organisms consumed by humans is condensed into one parameter — the bioaccumulation factor Bp. **Bioaccumulation** refers to the **build-up of radionuclides in an organism** over time, due to continuous uptake from the environment faster than elimination.

Factors Affecting Bioaccumulation

1. **Chemical properties of the radionuclide** – such as solubility, ionic form, and complex formation ability
2. **Type of organism** – differences in metabolism, age, body size, and trophic level
3. **Environmental conditions** – pH, temperature, salinity, and the presence of other binding substances
4. **Exposure time** – the longer the exposure, the greater the potential for accumulation.

Bioaccumulation Factor

The bioaccumulation factor is defined as the **ratio between the concentration of a substance in an organism and its concentration in the surrounding environment (usually water):**

$$\text{BAF} = \frac{C_{organism}}{C_{water}}$$

where:

- $C_{organism}$ =concentration of the radionuclide in the organism's tissue (e.g., Bq/kg)
- C_{water} =concentration of the radionuclide in water (e.g., Bq/L)

Meaning of BAF Values

- **High BAF** → the organism efficiently accumulates radionuclides even when concentrations in water are low
- **Low BAF** → accumulation in the organism is low even if the environment is contaminated.

Bioaccumulation Factor

For example, the radionuclide **cesium-137 (^{137}Cs)** has chemical properties similar to potassium, making it easily absorbed into fish muscle tissue. If the ^{137}Cs concentration in water is 1 Bq/L and in fish tissue is 1000 Bq/kg, then:

$$BAF = \frac{1000}{1} = 1000$$

This means the fish has a high bioaccumulation potential for cesium.

The bioaccumulation factor is used in **environmental radiological risk assessment** to:

- Estimate **internal radiation exposure** for biota and humans (via the food chain)
- Determine the **potential transfer of radionuclides** between environmental compartments (water → biota → humans)
- Support **modeling of radionuclide dispersion and ecological impacts**.

Transfer Factor

The **Transfer Factor (TF)** quantifies the transfer of radionuclides from one environmental medium (e.g., soil or water) to a biological component (e.g., plant, animal).

❑ **Definition:**

$$TF = \frac{C_{organism}}{C_{environment}}$$

Where:

- $C_{organism}$ =concentration of radionuclide in biota (Bq/kg fresh or dry weight)
- $C_{environment}$ =concentration in soil, water, or food (Bq/kg or Bq/L)

Example:

If Cs-137 concentration in grass = 500 Bq/kg and in soil = 5000 Bq/kg,
then $TF = 0.1$.
A higher TF indicates that the radionuclide is **readily taken up and transferred** within the ecosystem.

Transfer Factor

Radionuclide	Soil → Plant TF	Plant → Animal TF	Notes
Cs-137	0.01–0.1	0.1–0.5	Mimics K^+, easily mobile
Sr-90	0.05–0.2	0.3–0.7	Mimics Ca^{2+}, accumulates in bones
I-131	0.01–0.05	0.01–0.1	Concentrates in thyroid tissue
U-238	<0.01	<0.01	Low mobility; mostly retained in soil
Pu isotopes	<0.001	<0.001	Strongly adsorbed to soil; poor uptake

Biomagnification is the progressive **increase in radionuclide concentration** along successive trophic levels of the food chain.
For example:

1. **Water** → contains Cs-137 (0.01 Bq/L)
2. **Algae** → 1 Bq/kg
3. **Fish** → 50 Bq/kg
4. **Predatory bird** → 200 Bq/kg

Thus, even low environmental concentrations can result in significant doses at the top of the food chain (including humans).

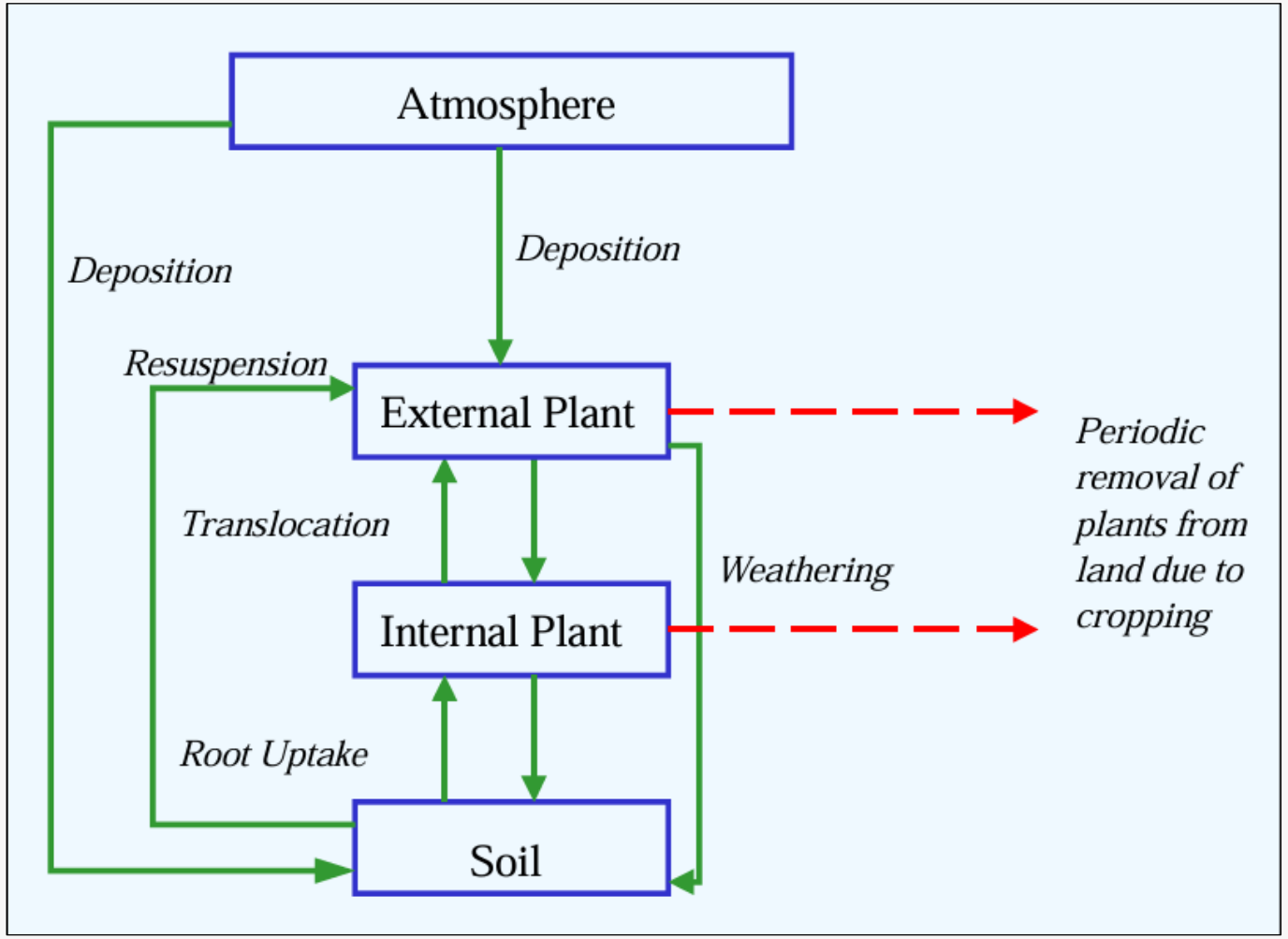
Biological Half-Life

Each radionuclide has a **biological half-life (T_β)** — the time required for half of the radionuclide to be eliminated from the organism through excretion or metabolism.
This is distinct from the **physical half-life (T_p)** of radioactive decay.
The **effective half-life (T_e)** combines both:

$$\frac{1}{T_e} = \frac{1}{T_p} + \frac{1}{T_b}$$

Short biological half-lives (e.g., I-131 in humans ≈ 7 days) limit long-term accumulation, while long ones (e.g., Cs-137 in muscle ≈ 70 days) promote persistence in organisms.

Transfer to Terrestrial Plants



Radionuclides intercepted by and retained on vegetation may result from fallout, washout, rainout, irrigation with contaminated water or deposition of suspended matter. External deposits can be taken up by foliar absorption into plants radionuclides may also be incorporated by uptake from soil through roots, followed by internal redistribution of radionuclides within plant. reduction of radionuclide concentrations in vegetation may occur reduction of radionuclide concentrations in vegetation may occur through radioactive decay, growth dilution, wash-off externally deposited radionuclides, leaching and soil fixation, grazing and harvesting

IAEA SRS 19, 2001

Environmental Transport Model

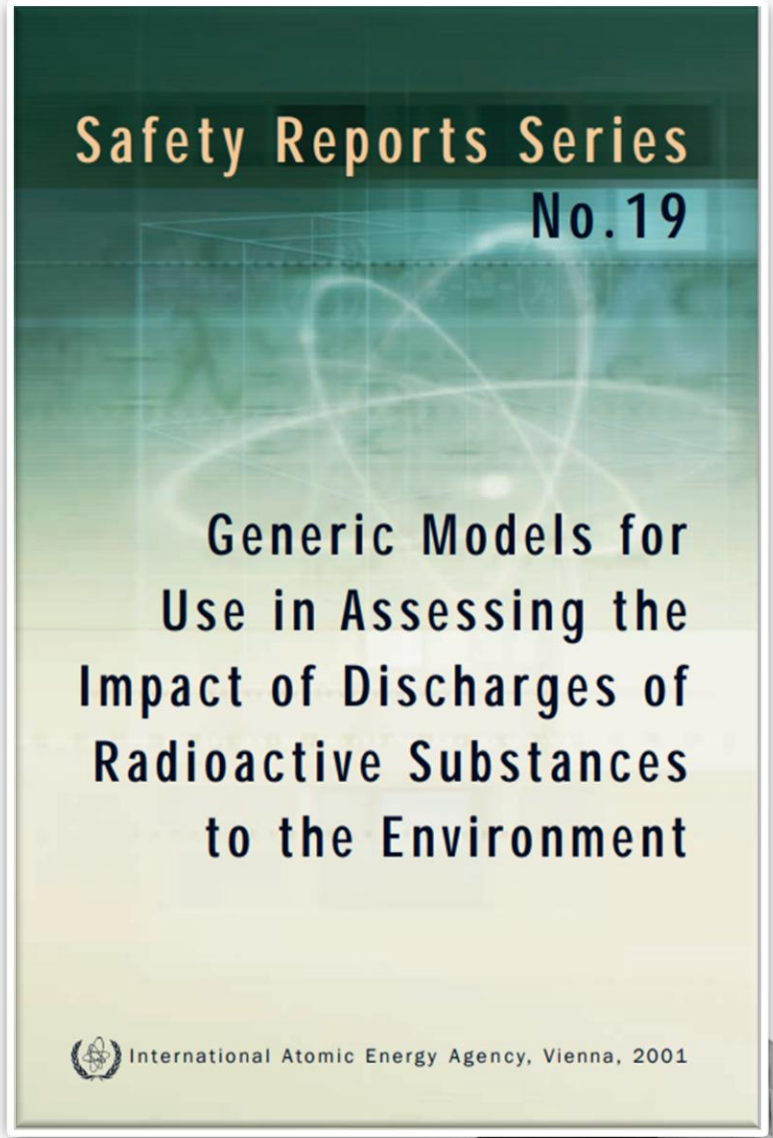
Surface Water

The generic methodology is based on analytical solutions to advection–diffusion equations describing radionuclide transport in surface waters with steady state uniform flow condition

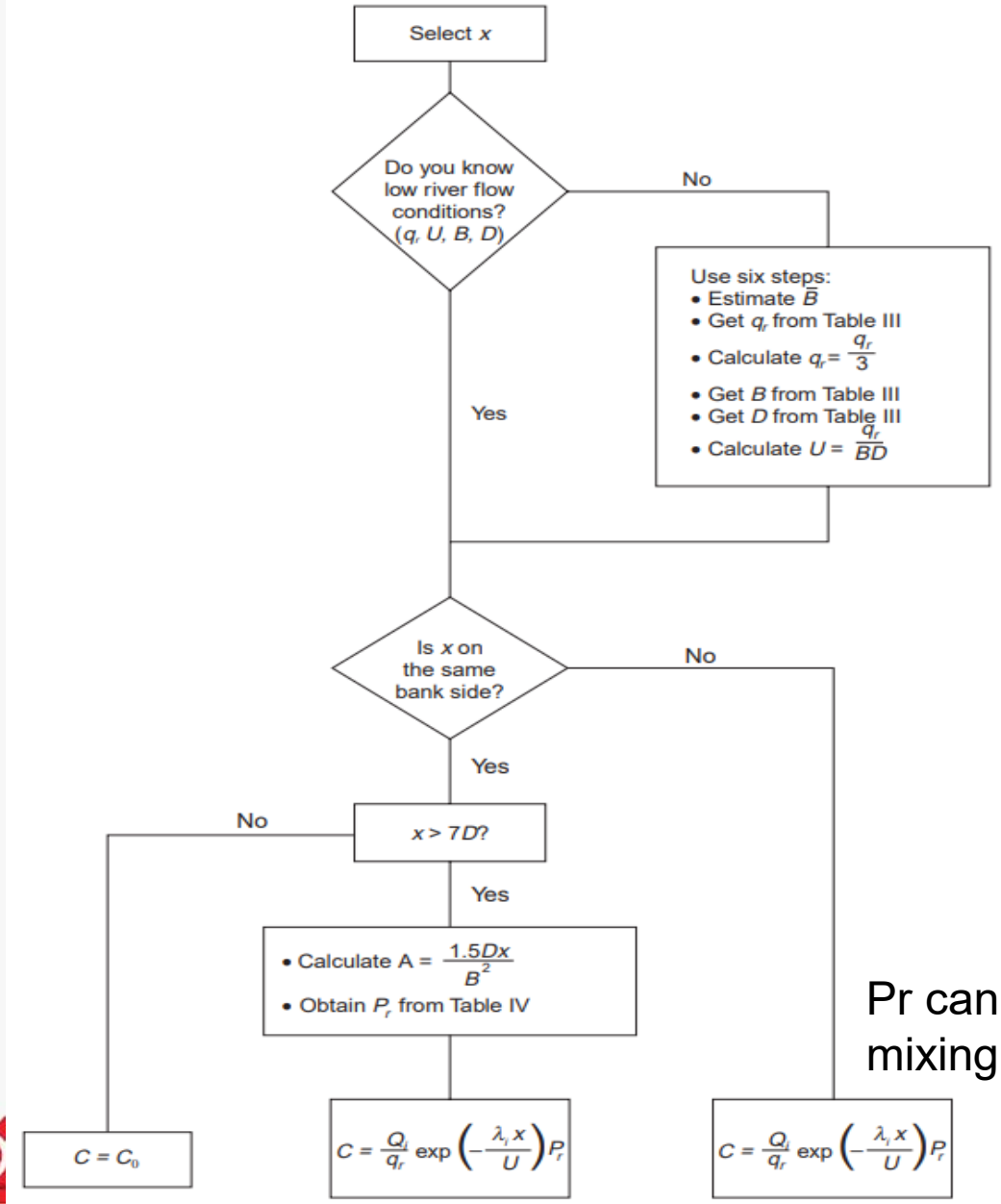
As a result of the simplifying assumptions implicit in its derivation, this generic methodology strictly applies only if the following conditions are satisfied:

- ✓ The surface water geometry (e.g. river cross-section, shoreline) does not change greatly with distance;
- ✓ The flow characteristics (e.g. flow velocity, water depth) do not change significantly with distance or with time;
- ✓ Radionuclides in water and sediment, under the in water and sediment, under the conditions of a routine, long term release, can be considered to be in equilibrium.

This approach is often used to assess the distribution of contaminants in surface waters.



Procedure for Calculating Radionuclide Concentrations in Water Resulting from a Discharge into Surface Water



Basic river characteristics required for calculations

1. River width B (m)
2. Longitudinal distance from the release point to a potential receptor location x (m)
3. Radionuclide decay constant li (s^{-1})

$$C_{w,\,\mathrm{tot}} = \frac{Q_i}{q_r}\exp\left(-\frac{\lambda_i x}{U}\right) = C_t$$

$C_{w,\,tot}$: total radionuclide concentration in water (Bq/m^3)
Q_i : average discharge rate for radionuclide i (Bq/s)
q_r : mean river flow rate (m^3/s)
λ_i : radioactive decay constant (s^{-1})
X : distance between the discharge point and the receptor (m)
U : net freshwater velocity (m/s)

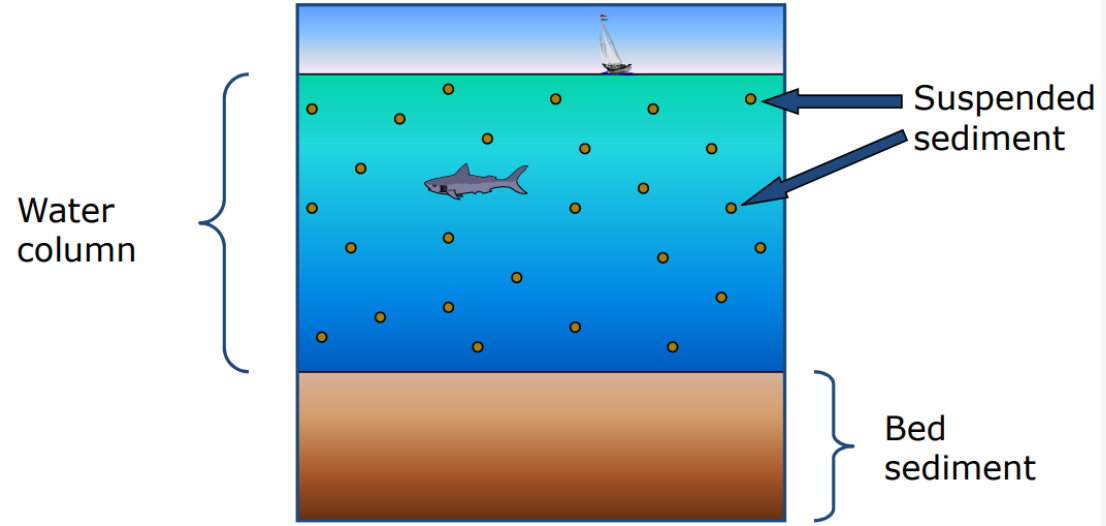
Pr can be regarded as a correction factor for the partial mixing

RADIONUCLIDE CONCENTRATION DUE TO SEDIMENT EFFECT

Radionuclide concentration in water

$$C_{w,s} = \frac{C_{w,\,\mathrm{tot}}}{1 + 0.001\,K_d S_s}$$

S_s is a suspended sediment concentration (kg/m^3 or g/L)



Radionuclide concentration in suspended sediment

$$C_{s,w} = \frac{0.001 K_d C_{w,\,\mathrm{tot}}}{1 + 0.001 S_s K_d} = 0.001 K_d C_{w,s}$$

Radionuclide concentration in bottom sediment

$$C_{s,b} = \frac{(0.1)(0.001) K_d C_{w,\,\mathrm{tot}}}{1 + 0.001 S_s K_d} \times \frac{1 - e^{-\lambda_i T_e}}{\lambda_i T_e} = 0.1 C_{s,w} \times \frac{1 - e^{-\lambda_i T_e}}{\lambda_i T_e}$$

T_e is the effective accumulation time (s)

Radionuclide concentration in shore/beach sediment

$$C_{s,s} = \frac{(0.1)(0.001) K_d \times 60 \times C_{w,\,\mathrm{tot}}}{1 + 0.001 S_s K_d} \times \frac{1 - e^{-\lambda_i T_e}}{\lambda_i T_e} = 60 C_{s,b}$$

TRANSPORT OF RADIONUCLIDES THROUGH AQUATIC FOOD CHAINS

Ingestion of radionuclides in foods can be an important contributor to the total dose received by an individual or population group. An estimate of the radionuclide concentration is needed to assess such doses. Radionuclides discharged into the aquatic environment are also assimilated by living organisms pass along the aquatic food chains and eventually reach humans

❑ Basic Model

are used to describe the transport of radionuclides radionuclides from liquid discharges to aquatic foods generally take the form :

$$C_{af,i} = C_{w,i} B_p / 1000$$

$C_{af,i}$: Concentration of radionuclide i in aquatic food p (Bq/kg)
$C_{w,i}$: Concentration of dissolved radionuclide i in water (Bq/m^3)
B_p : Equilibrium ratio of the concentration of radionuclide i in aquatic food p to its dissolved concentration in water (Bq·kg^{-1}/Bq·L^{-1}, or L/kg), known as the bioaccumulation factor
1000 is the conversion factor from m^3 to L.

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Atmospheric Radionuclide Concentration

$$C_A = \frac{P_p Q_i}{V}$$

The simplest and most pessimistic screening technique is to assume that the radionuclide concentration at the point of interest (often referred to as the receptor location) is equal to the atmospheric radionuclide concentration at the point of release

where

- CA is the ground level air concentration at downwind distance x (Bq/m3),
- Qi is the average discharge rate for radionuclide i (Bq/s),
- V is the volumetric air flow rate of the vent or stack at the point of release (m3/s),
- Pp is the fraction of the time the wind blows towards the receptor of interest (dimensionless)

The Gaussian Plume Model

$$C_A(x,y,z) = \frac{Q_i}{2\pi\sigma_y\sigma_z u}\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{\exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}$$

Where :

- CA(x,y,z) is the air concentration (Bq/m3) at a point (x,y,z) downwind of the release;
- x is the downwind distance (m);
- y is the crosswind distance (m);
- z is the height above ground (m);
- Qi is the release rate for radionuclide i (Bq/s);
- Σy ,σz are the diffusion parameters (m), which are a function of downwind distance x and atmospheric stability;
- u is the mean wind speed (m/s);
- H is the height of release (m).

(Radiation Protection Division, 2009)

The Gaussian Plume Model

The Gaussian plume model is limited to rather simple dispersion situations.

- Dispersion over flat, non-complex terrain;
- Short range transport (about 100 m to 20 km downwind);
- Steady state meteorological conditions;
- No elevated temperature inversions;
- Quasi-continuous releases;
- Transport and mixing in the lee of isolated point sources;
- Non-depositing materials, such as noble gases

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BRIN
BADAN RISET
DAN INOVASI NASIONAL

THANK YOU FOR YOUR KIND ATTENTION

ご静聴ありがとうございました