Chapter 8 Radioactive Isotopes and Radiation Generator

Section 1 Introduction

1 What is Radiation?

Radiation is an electromagnetic wave or particle beam that has the ability to directly or indirectly ionize air and is designated by a Cabinet Order (Atomic Energy Basic Act, Article 3, Item 5; see Section 3). In addition, it is sometimes called the "ionizing radiation" due to the ionizing ability of the radiation (Article 2 of the Regulation on Prevention of Ionizing Radiation Hazards, Industrial Safety and Health Act).

Radiation is characterized by its ability to penetrate, ionize, and excite substances, and is widely used in medicine and research. Humans are unable to detect radiation using the five senses (sight, smell, taste, hearing, and touch); therefore, they can be **overexposed to radiation in the absence of adequate knowledge of radiation safety handling**.

The use of radiation emitted from radioisotopes and radiation generator may greatly contribute to research and industrial development, but there exist risks of being exposed to radiation, creating radiation hazards on the human body (See Section 2). This was revealed in an unfortunate critical accident that occurred at the Tokai Plant of JCO Co., Ltd. in Ibaraki Prefecture on September 30, 1999, which resulted in casualties due to widespread public radiation exposure.

As you know it is necessary to prevent accidents during research using radiation. However, to handle disaster management such as earthquakes or fire, **radiation workers must have a basic understanding of the characteristics of radiation, the differences between radiation and radioactivity, radiation detection methods, and radiation injury prevention methods.**

The Nagaoka University of Technology conducts experiments related to radiation only during the lectures on radiation-related experiments and safety, but those who wish to deepen their understanding may receive further education at the Radioisotope Research Center, Extreme Energy-Density Research Institute (EDI), and the Department of Nuclear Technology.

2 Where can it be used?

The Act on the Regulation of Radioisotopes (hereinafter referred to as the "RI Law") strictly regulates the locations where radioisotopes (RI) and Radiation generator can be used to prevent the damages caused by radiation exposure. In principle, these devices may not be used except in facilities created for the purpose of handling radioisotopes.

Japan's Nuclear Radiation Authority has approved Nagaoka University of Technology **for the use of radioisotopes at the Radioisotope Center and Radiation generators at the Extreme Energy-Density Research Institute (EDI) and Faculty Building for Nuclear System Safety Engineering and System Safety.**

The laboratory facilities and daily usage limit for each type of radioisotope are established by the RI Law; the usage location and usage frequency of the Radiation generators are also provided by this law. **When engaging in radiation-related studies, researchers must devise an experimental plan in advance, and make coordinated adjustments with other researchers so that the usage quantity and frequency are not exceeded.** These regulations ensure the safety of radiation workers and the public who reside outside the controlled area.

3 Who can use it?

At the Nagaoka University of Technology, radiation access is limited to the people who comply the following criteria: registered as a radiation worker as specified in the Nagaoka University of Technology Regulations on Radiation Injury Prevention (referred hereafter as "prevention regulations"); received the necessary education, training, and special health examinations; and received approval from the Nagaoka University of Technology Radiation Safety Committee (**radiation worker,** see Section 3).

4 What can use?

Only Japan's Nuclear Radiation Authority approved type, quantity, and format of radioisotopes (both sealed and unsealed radioactive sources) and Radiation generator, whose list as per February 12, 2012, is given in Table 8-1, is used by the Nagaoka University of Technology.

Table 8-1 Radioisotopes and Radiation generator that can be used at the Nagaoka University of Technology

Radioisotope	Unsealed radioactive source	^{3}H, ^{10}Be, ^{14}C, ^{31}Si, ^{32}P, ^{35}S, ^{51}Cr, ^{55}Fe, ^{57}Co, ^{59}Fe, ^{85}Sr, ^{99}Tc, ^{106}Ru, ^{125}I, ^{129}I, ^{131}I, ^{133}Ba, ^{137}Cs, ^{139}Ce, ^{141}Ce, ^{144}Ce, ^{147}Nd, ^{152}Eu, ^{169}Yb, ^{237}Np, ^{241}Am, ^{242}Cm, ^{243}Cm, ^{243}Am, ^{244}Cm, ^{252}Cf (Purpose of use: Research on chemical reactions)
	Sealed radioactive source	^{57}Co 370MBq, ^{57}Co 740MBq, ^{60}Co 37MBq, ^{109}Cd 370MBq, ^{113}Sn 1.11GBq, ^{137}Cs 370MBq, ^{144}Ce 370MBq, ^{170}Tm 370MBq, ^{204}Tl 185MBq, ^{241}Am 370MBq, ^{252}Cf 18.5MBq (Purpose of use: Research on meters and instruments, and chemical reactions)
Radiation Generator		Cockcroft–Walton accelerator, 1 unit (Purpose of use: Basic experiments on the generation and application of high-intensity pulsed ion beams) Cockcroft–Walton accelerator, 1 unit (Purpose of use: Basic experiments on the generation and application of high-intensity electron beams) Cockcroft–Walton accelerator, 1 unit (Purpose of use: Material analysis and development using high-energy ion beams) Cockcroft–Walton accelerator, 1 unit (Purpose of use: Composition analysis by irradiating samples with an ion beam)

Section 2 Effects of radiation on the human body

Humans are constantly exposed to tiny (traces) amounts of radiation in their regular environment. This radiation is called natural background radiation and includes radiation from cosmic rays, neutrons, uranium-238, thorium-232, radium-226, radon-222, and potassium-40. Although the amount varies slightly based on the region, the average radiation dose (effective dose) on the human body from the background radiation is approximately 2 millisieverts (mSv) per year. In addition, humans may be exposed to artificial radiation, primarily during medical treatments such as X-ray imaging. The National Institute of Radiological Sciences (NIRS-QST) has published on its website a quick view of the various radiation exposure we encounter in daily life (Figure 8-1: https://www.qst.go.jp/uploaded/attachment/1572.pdf).

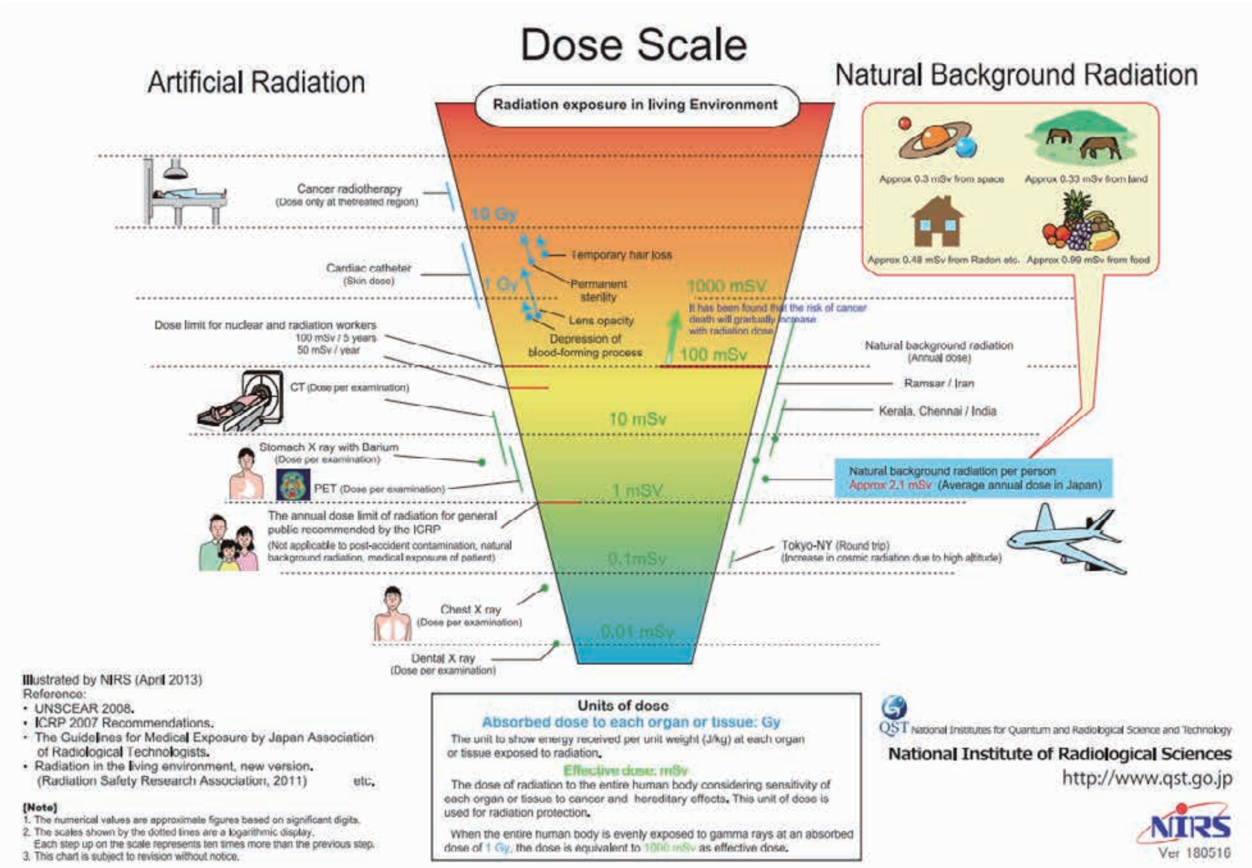

Figure 8-1 Relationship between daily life and radiation

The RI Law stipulates the limit for the effective dose of radiation on workers using radiation for research purposes as 100 mSv per 5 years and 50 mSv per year. This amount is approximately 10–25 times the dosage received from the background radiation.

Radiation is generally considered to cause injury to the human body. Damages develop on the atomic, molecular, cellular, tissue, organ, and individual levels with the advancement in exposure. In addition, some radiation damage may affect the offspring.

This section describes the effects of radiation on the human body, and the differences in effect based on radiation dose and exposure method.

1 Categorization by timing of onset of radiation injury

Radiation injury can be broadly divided into two categories—**somatic** and **genetic effects—**based on to whom and when the impact occurs (Figure 8-2). Somatic effects appear in the individual exposed to the radiation, and can be categorized into acute effects, which appear immediately (2 to 3 months) after the exposure, and late (delayed) effects, which appear over a long period (from 10 months to several years) after the exposure. Genetic effects have not yet been confirmed in humans. It typically developed in not individuals exposed to the radiation but their children or grandchildren. The genetic mutation transmits to the descendants and express itself as a somatic effect in the offspring.

- Acute effects: Appears when one is exposed to a large amount of radiation in a short time. Radiation exposure to a wide area of the body causes symptoms such as fever, bleeding, decrease in leukocytes, diarrhea, vomiting, dehydration, skin erythema and ulcers, and hair loss.
- Late effects: The biggest concern is carcinogenesis. The main types of cancer caused by radiation exposure in humans are blood, skin, thyroid, breast, and bone tumors. Other diseases include cataracts.

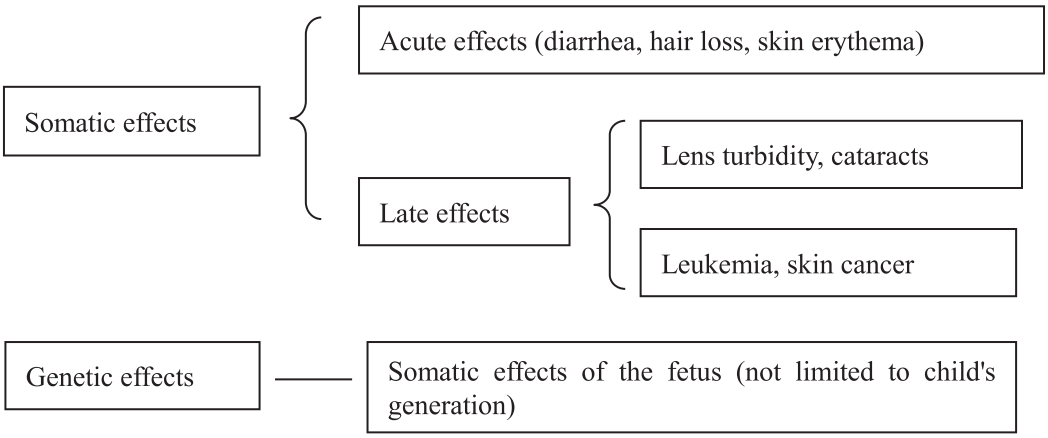

Figure 8-2 Somatic effects (acute effects/late effects) and genetic effects of radiation exposure

2 Categorization by mode of exposure

(1) External and internal radiation exposures

Radiation exposure is categorized based on whether the radiation source is inside or outside the body. **Internal exposure** occurs when the body is exposed to radiation from a radiation source inside the body, while **external exposure** occurs when the body is exposed to radiation from a source outside the body. The degree of radiation injury varies based on type of radiation. Internal exposure to alpha ray emitting radionuclides requires special attention as nearly all radioactive energy contributes to severe damages. Internal exposure causes constant radiation exposure until the radiation source is expelled outside the body. Internal exposure is evaluated using the biological half-life, or the time until the ingested radioisotope is excreted, and the effective half-life calculated from the physical half-life of the radioisotope.

Time, distance, and shielding measures minimize exposure to external radiation. Prevention of **inhalation, ingestion, and percutaneous absorption** is required to minimize internal exposure.

(2) Acute and chronic radiation exposures

Acute radiation exposure refers to exposure to a high dose of radiation in a very short period of time, and **chronic radiation exposure** refers to chronic or intermittent exposure to radiation over a long period of time. There may be differences in the degree of radiation injury between acute and chronic exposures, even if the exposure dose is the same. This is because the recovery power of cells and tissues to bounce back from damage exceeds the radiation damage. In the field of radiation protection, humans recover from low-dose radiation exposures measuring 0.1 Gy or less per hour in absorbed dose rate (Gy, or the radiation energy absorbed by tissue per unit time) without the development of radiation injury.

(3) Partial and total body radiation exposures

Partial body radiation exposure (localized radiation exposure) refers to the exposure of a part of the body, while total body radiation exposure refers to exposure to the entire body or a large part of the body. The effects develop differently depending on the exposure area and volume. For example, skin erythema may occur if the palm is exposed to 10 Gy, although recovery is possible. However, a total body exposure of 10 Gy might be fatal.

This occurs because, in a partial body exposure, only the tissues and organs exposed to the radiation are affected. However, in a total body exposure, the radiation effects start in tissues and organs with high radiosensitivity, then develop in all tissues and organs with the increase in radiation dose.

Table 8-2 shows the radiosensitivity of each tissue. Cells are most radiosensitive during the differentiation process, wherein undifferentiated fetal cells transform into specialized cells of adult tissue. Certain fetal cells are present and continue to differentiate in adulthood, such as those found in the bone marrow, lymph glands, epidermis, and reproductive glands; these cells have high radiosensitivity. **In other words, tissues and organs with active cell division and high metabolism have high radiosensitivity.** Hematopoietic organs, lymphoid tissues, and reproductive glands are the most sensitive; particularly, root stem cells are highly radiosensitive. Moreover, blood vessels, skin, and cells of the central nervous system are moderately resistant, and muscle, bone, and peripheral nerves are highly resistant to radiation.

(4) Radiation exposure during pregnancy and effects on the fetus

Even non-regenerative cells in adult tissues are **highly sensitive as fetal tissues** because they undergo cell division during the development. Table 8-3 shows the effects of radiation on the fetus. Women who are pregnant or may be pregnant should take note of the radiation dosage to which they are exposed while handling radiation.

3 Categorization by threshold

The frequency and probability of radiation injury are related to the radiation dose. The minimum dose at which the effects of radiation appear is called the **threshold dose**. The International Commission on Radiological Protection (ICRP) categorizes radiation effects based on the presence of threshold as stochastic effects or harmful tissue reactions (Table 8-4 and Figure 8-3). The radiation dose limit for radiation workers is set by a policy to prevent the occurrence of harmful tissue reactions and limit the occurrence of stochastic effects to an acceptable level.

Table 8-2 Radiosensitivity of tissue

Radiosensitivity	Tissue
Highest	Lymphoid tissue (thymus, spleen), bone marrow, reproductive glands (testes, ovaries)
High	Small intestines, skin, capillaries, crystalline lens
Medium	Liver, salivary glands
Low	Thyroid, muscles, connective tissue
Lowest	Brain, bones, nerve cells

(Cited from *Hoshasen Gairon*)

Table 8-3 Radiation effects on fetus

Fetal period	Term	Radiation impact	Threshold <Gy>
Germinal stage	Fertilization until 8 days after fertilization	Embryo loss	0.1
Embryonic period	9 days to 8 weeks after fertilization	Congenital malformation	0.15
Fetal stage	8 weeks to 25 weeks after fertilization 8 weeks to 40 weeks after fertilization	Mental development retardation Fetal growth restriction	0.2–0.4 0.5–1.0
All terms	—	Cancer and genetic effects	—

(Cited from *Hoshasen Gairon*)

Table 8-4 Categorization of radiation effects from the perspective of radiation protection

Type	Goals of radiation protection	Threshold	Factors that change with increased radiation dosage	Example
Stochastic effects	Limit occurrence to an acceptable	Does not exist	Probability of occurrence (frequency)	Carcinogenesis Genetic effects
harmful tissue reactions	Prevent all occurrences	Exists	Severity	Cataracts, skin erythema, hair loss, infertility

(Cited from ICRP No. 26)

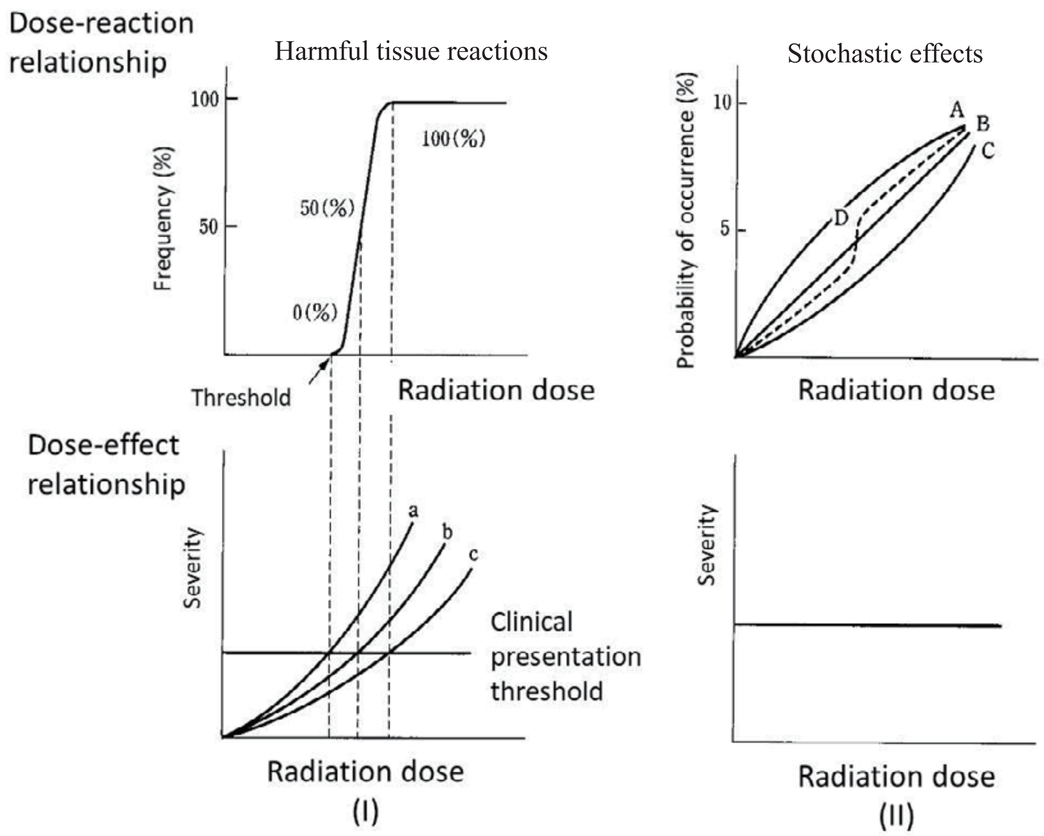

Figure 8-3 Relationship between radiation dose and radiation effects**.** Cited from the Foundations of Radiation Handling Safety)

4 Categorization by type of radiation

As radiation traverses an organism, the interaction of radiation with matter energizes the matter. As mentioned above, almost all radiation effects to the human body are considered injury. The degree of injury varies significantly according to type of radiation.

Linear energy transfer (LET) refers to the energy per unit distance that the radiation transfers to the substances along its path. Among radiations of the same energy, the LET is larger for alpha rays than beta rays or gamma rays. Generally, gamma rays (X-rays) and beta rays are considered to be **low-LET forms of radiation**, while neutron rays, alpha rays, proton beams, and heavy particle beams are **high-LET forms of radiation**.

Section 3 Radiation, RI, and radiation-emitting devices

1 Radiation

The RI Law is a law enacted to regulate the use of RI and Radiation generator and the disposal of RI-contaminated waste to prevent radiation damage and ensure public safety. **Radiation subject to regulation is "electromagnetic waves or particle rays that have the ability to ionize air directly or indirectly, as specified below."**

(1) Alpha rays, heavy particle beam, proton beam, and other heavily-charged particle beam and beta rays
(2) Neutron beam
(3) Gamma rays and Characteristic X-ray (limited to characteristic X-rays generated by the orbital electron capture process)
(4) Electron beams and X-rays with energies 1 MeV or more

Note) Electron beams and X-rays with energies less than 1 MeV are subject to the Regulation on Prevention of Ionizing Radiation Hazards, and still require radiation protection measures. For details, see “Chapter 9: X-rays and X-ray generators.”

Below, we briefly describe the interaction between substances and typical radiation (alpha rays, beta rays, gamma rays (X-ray), and neutron beam).

1. Alpha rays

Alpha rays consist of two protons and two neutrons bound together into a particle identical to a helium nucleus. As this is heavier particle than the beta rays, which is similarly electrically charged, they travel in nearly straight paths and has minimal bremsstrahlung losses caused by electron interaction. The specific ionization increases with the decrease in velocity, reaching maximum energy of 370 keV before it stops. **The thickness of the medium through which the radiation can penetrate (range) varies by the type of particle, its original energy of motion (kinetic energy), and the medium through which it travels. The range of alpha rays emitted from an ordinary radioisotope is only a few centimeters in the air.** Due to the short range, one sheet of paper is sufficient to shield alpha rays, and the risk of external exposure is extremely low. However, when alpha-ray-releasing nuclides are taken inside the body, the particle can release enormous energy to a narrow region in the living cells. The range of alpha rays in a living body, at several dozen μm, is shorter than that in the air. However, there is a risk of serious local damage. For these reasons, **the inhalation, ingestion, or absorption of alpha-ray-releasing nuclides into the body is extremely dangerous, and strict measures for safety management are taken.**

2. Beta rays

Beta rays is an electron beam emitted from the atomic nucleus. Beta rays includes β+ (producing positrons) and β- decays (producing electrons); both rays release same charged particles that differ in their sign. The primary interaction of beta rays and matter are (1) excitation and ionization of atoms by Coulomb force and (2) **braking X-ray (bremsstrahlung) generation** through interaction with atomic nuclei. A positron that loses energy due to its interaction with matter undergoes a **pair annihilation** with an electron and produces two photons. In addition, beta rays also undergo **backscattering**, where the particles undergo excitation, ionization, and scattering, and exit from the same direction as it entered. Hence, shielding measures must be taken for the scattered rays.

When selecting a shielding measure for beta rays, the bremsstrahlung X-ray radiation must be considered. **A suitable method would be to shield the high-energy beta rays using a substance with a small atomic number (such as acrylic or aluminum), and shield the bremsstrahlung X-rays with iron or lead.**

3. Gamma rays (X-ray)

Gamma rays are photons emitted when a nucleus transitions from an excited energetic state to a lower-energy state. As photons have no electric charge, their interaction when passing through matter is different from that of charged particles, such as alpha and beta rays. Interactions of photons with matter include Thomson scattering, photoelectric effect, Compton effect, and electron-positron pair production.

The difference between gamma rays and X-rays stems from the generation process. In gamma rays, rest energy is given off as photons through a nuclear reaction or elementary particle reaction, while X-rays are produced when the extra energy generated by charged particles as they change from motion to restricted states is emitted as photons. These rays are not classified by photon energy.

Shielding measures for gamma rays include the use of an appropriate substance corresponding to the photon energy. In general, lead or a similar substance is suitable for radiation shielding as gamma rays (X-rays) have large interaction with high-density materials.

4. Neutron beam

Neutrons are electrically neutral particles. They are unstable particles with a half-life of ten and several minutes; when they decay into a proton and electron, interactions occur similar to beta rays and alpha rays described previously. In addition, the interactions of neutrons with matter include a) elastic scattering, b) inelastic scattering, c) charged particle emission reaction, d) capture reaction, and e) nuclear fission. In an elastic scattering, neutrons lose more energy when they collide with smaller atomic nuclei. Therefore, **substances such as paraffin, concrete, and water, which contain several hydrogen atoms, are suitable to shield neutrons.**

In b)–e) effects, the interactions may cause the atomic nucleus to emit protons and γ-rays, or fission may occur in heavy atomic nuclei such as uranium. Such interactions also need to be considered for neutron shielding.

2 RI (Radio Isotope: Radioactive Isotopes)

The radioisotopes regulated by the RI Law are **isotopes that release radiation (such as phosphorus-32 and cobalt-60), its compounds, and their inclusions (including those equipped in the devices). RI Law regulates the quantity and concentration of radiation-emitting isotopes used in experiments when they exceed the quantity (lower limit) and concentration specified for each type by Japan's Nuclear Radiation Authority (Table 8-5).**

Table 8-5 Sample quantity and concentrations of radioactive isotopes

Column 1		Column 2	Column 3
Isotopes that release radiation		Quantity (Bq)	Concentration (Bq/g)
Nuclide	Chemical form		
^{3}H		1×10^{9}	1×10^{6}
^{7}Be		1×10^{7}	1×10^{3}
^{10}Be		1×10^{6}	1×10^{4}
^{11}C	Monoxides and dioxides	1×10^{9}	1×10^{1}
^{11}C	Not monoxide or dioxide	1×10^{6}	1×10^{1}

However, the regulation scope of the RI Law excludes items 1–5 below.

1. Nuclear fuel and source materials specified by the Atomic Energy Basic Act.
2. Pharmaceuticals and raw materials or ingredients specified in the Act on Securing Quality, Efficacy and Safety of Products Including Pharmaceuticals and Medical Devices that are present at manufacturing plants approved by this Act.
3. Drugs specified in the Act on Securing Quality, Efficacy and Safety of Products Including Pharmaceuticals and Medical Devices used in clinical trials at hospitals or clinics regulated by the Medical Care Act.
4. In addition to the above, drugs used by positron radio tomography equipment for image diagnosis or other drugs administered to persons receiving medical treatment or diagnosis, which are prepared at the hospitals performing the diagnosis or treatment, specified by the Nuclear Radiation Authority in consultation with the Minister of Health, Labour and Welfare.
5. Components equipped in the medical devices specified in the Act on Securing Quality, Efficacy and Safety of Products Including Pharmaceuticals and Medical Devices and the Nuclear Radiation Authority in consultation with the Minister of Health, Labour and Welfare or the Minister of Agriculture, Forestry and Fisheries.

3 Radiation Generator

The Radiation generator regulated by the RI Law are devices, such as cyclotron and synchrotron, that generate radiation by accelerating charged particles; these are listed as follows (devices whose maximum dose equivalent rate at a position of 10 cm from the surface is less than the dose equivalent rate set by the Nuclear Radiation Authority are excluded):

(1) Cyclotron
(2) Synchrotron
(3) Synchrocyclotron
(4) Linear particle accelerator
(5) Betatron
(6) Van de Graaff accelerator
(7) Cockcroft–Walton accelerator
(8) Other devices that generate radiation by accelerating charged particles and designated by the Japan's Nuclear Radiation Authority as necessary to take precaution against radiation damage.

4 Units of radiation

(1) Radioactivity

We often hear of "radioactivity" to indicate units of radiation. Radioactivity refers to the number of atoms decayed by the atomic nuclei of a radioactive isotope in a unit time, and one becquerel is defined as one atomic disintegration per second (Bq = s^{-1}).

Radioactivity describes traits, similar to speed or brightness, and does not directly identify the radioisotope or radioactive particles themselves. Media may use expressions such as "radioactivity leakage from nuclear power plants," but one must take care not to confuse radioisotopes, radiation, and radioactivity.

Prior to the becquerel (Bq), an older unit, Curie (Ci) was used to represent radioactivity, and measured the number of decays that occur in 1 gram of radium per second. One curie (1 Ci) is equal to 3.7×10^{10} Bq (radioactive decays per second).

(2) Radiation Dose

An absorbed dose measures the energy deposited by ionizing radiation in a unit mass of matter (1 kg) being irradiated, and is expressed as Gray (symbol: Gy; equal to joules per kilogram, J/kg).

The effect of radiation on the human body depends on the LET of the radiation. Radiation doses were devised to calculate the effects of various types of radiation on the human body on the same scale and to enable comparisons and combinations for the purpose of radiation protection.

Radiation dose = absorbed dose × radiation quality coefficient × correction coefficient

The radiation dose is determined for radiation protection, and the unit of radiation dose is Sievert (symbol: Sv, equal to joule per kilogram, J/kg).

Furthermore, equivalent doses are calculated considering differences in radio sensitivity of human tissues, and the effective dose is calculated by adding them.

(3) Electron volt

Radiation, as defined by the RI Law, includes "electron beams and X-rays with energies of 1 MeV or more." An eV is the measure of an amount of kinetic energy gained by a single electron accelerating from rest through an electric potential difference of one volt in vacuum, and is expressed as,

$$1 \langle eV \rangle = 1.602\times10^{-19} \langle J \rangle$$

1 MeV is equivalent to 1 million electron volts.

Section 4 Safety handling and usage procedures for RI and Radiation Generator

1 Safety handling

This serves as a handbook to explain the Nagaoka University of Technology Regulations on Radiation injury Prevention (prevention regulations) and the educational/training textbooks developed for the safe handling of RI and Radiation generator.

Prior to registration as a radiation worker, health examination and education/training are required for authorization to use RIs and Radiation generators. During use, radiation workers are obligated to maintain strict control of the radioactive source and record its receipt, delivery, usage, storage, transportation, and disposal. To prevent contamination and exposure, radiation workers must conduct an inspection of the equipment, work area, and floor surface before and after experiments, and measure the air-radiation dose rate during the experiment.

2 Usage procedures

To handle RIs and Radiation generator, one must register as a radiation worker specified in the prevention regulations.

The President will register the radiation workers pending a discussion with the Radiation Safety Committee and based on the results of the health examination and education/training. After registration, the radiation worker must perform a monthly measurement of radiation doses (using a "glass badge" radiation monitor) and undergo a health examination every six months or less.

3 Obtaining RI

RI procurement (for example, through purchase) requires permission from the chief radiation protection officer; hence, the purchase application form must be submitted to the Radioisotope Center Management Office. **RI may not be purchased or received without approval from the chief radiation protection officer.** If the RI is received after the application is submitted, the Radioisotope Center Management & Calculation Office will verify the application and notify the applicant. The applicant must obtain the radioisotope label and recording sheet from the Management & Calculation Office before using the RI.

Please note that, under the RI Law, the radiation worker is considered to be in possession of the RI even if the content of the container is used up and the radioactivity is almost completely attenuated; thus, recording obligations continue until the disposal process is complete. Delivery or disposal procedures are desirable for RIs that are not intended for long-term use.

4 Education and training

To ensure the safe handling of RIs and Radiation generators, radiation workers who have access to controlled areas must undergo **education** and **training** in each period (not exceeding one year) to prevent radiation injury. Radiation workers and new registrants will be notified about education and training sessions and must attend them.

5 Entry and precautions in Radiation Facilities

Radiation workers must be familiar with the prevention regulations and consider the following (1) through (7) when engaging in radiation work at facilities where radiation is used. **Tours** must be conducted by first obtaining permission from the radiation safety officer, undergoing education and training for a temporary visitor, and under the guidance of a radiation worker. Please note that the temporary visitor cannot operate or handle radioactive materials or radiation.

(1) Read the list of precautions posted in the radiation facility.

(2) Eating, drinking, smoking, and make-up are prohibited in the controlled area.

(3) Don't bring unnecessary items into the controlled area. In particular, wireless devices such as mobile phones must be turned off, as they may interfere with the functions of the personal radiation dosimeter.

(4) In the contamination inspection room, change into special slippers and wear a yellow lab coat.

(5) The personal radiation dosimeter (Figure 8-4) measures the radiation dose in the controlled area. Men should wear the dosimeter on the chest and women on the abdomen. Please roll up or lift the hem of any clothing that comes into contact with the floor.

(6) Articles inside the controlled area may only be removed if the RI surface contamination has been measured and confirmed to be less than one-tenth of the surface density limit.

(7) Before leaving the controlled area, hands, feet, and clothing must be inspected for contamination using the equipment (Figure 8-5). If contamination is detected, please seek instructions from the radiation safety

officer or radiation workers and perform appropriate decontamination.

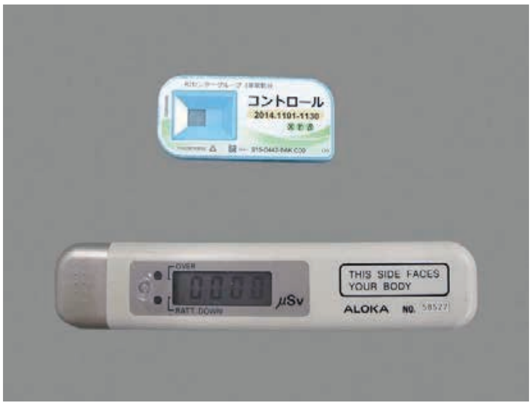

Figure 8-4　Personal radiation dosimeter

Figure 8-5　Contamination detecting equipment for hands, feet, and clothing (hand-foot-clothing contamination monitor, HFC)

6 Detection of radiation

When inspecting the contamination of the equipment and work area and measuring the air-radiation dose rate during the experiment, it is necessary to select equipment that is well suited to the radiation used.

Commonly used radiation measuring devices include a portable ion chamber, NaI scintillation, and GM survey meters.

Because a survey meter may not detect alpha and soft beta rays (beta rays with weak energy), it is advisable to use the smear method to inspect and measure contamination on the equipment and work area caused by radiation-emitting nuclei. Commonly used measuring devices include a liquid scintillation counter or gas flow meter.

Further, a NaI (Tl) detector or a Ge detector is used to identify the radioisotope of the contaminated part. Figure 8-6 shows the Cobalt-60 (^{60}Co) spectrum made by the germanium-based semiconductor detector and wave height analysis system (main photon energy and emission ratio of 1.173 MeV-100%, 1.333 MeV-100%; from *Radioisotope Pocket Data Book*).

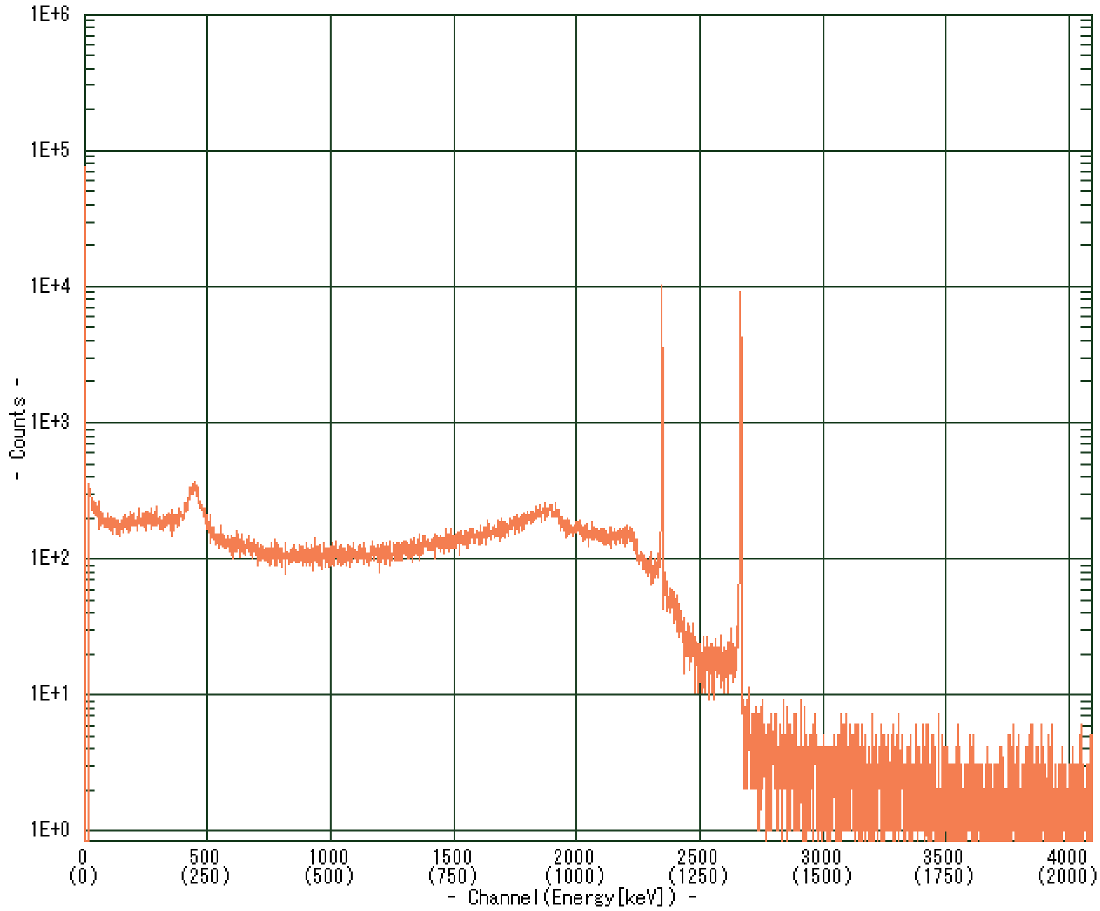

Figure 8-6 Cobalt-60 (^{60}Co) spectrum

(Measured using a semiconductor radiation detector and wave height analysis system)

7 Radiation protection

Basic measures for radiation protection include the following:

- Set an experimental plan and conduct sufficient preliminary experiments (cold run)
- Prevent external exposure
- Prevent internal exposure
- Do not work alone
- Perform contamination inspection before and after tasks and dosimetry during the tasks

Among these protection methods, we describe the prevention of external exposure and internal exposure below.

(1) Prevention of external exposure

There are three principles to prevent external radiation exposure-shielding measures, distance, and time.

A) Protection using shielding measures

The distance by which radiation permeates through matter differs according to radiation type and energy. Thus, shielding measures must be used to reduce radiation dosage maximally.

Because beta rays emits braking (bremsstrahlung) X-rays, it must be shielded with an acrylic plate.

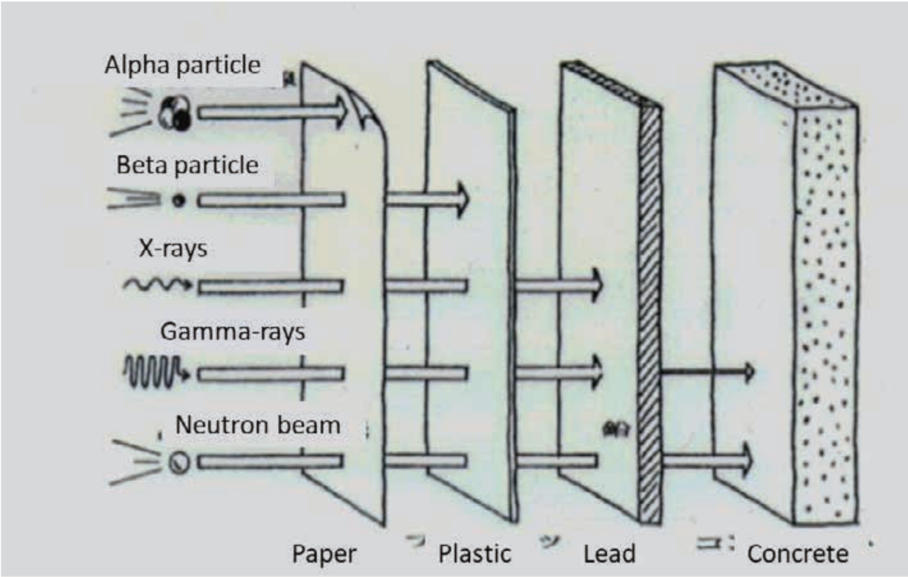

Figure 8-7 An example of shielding by radiation

B) Protection through distance measures

Because the radiation intensity is inversely proportional to the square of the distance, the radiation dose decreases sharply as the distance increases from the radiation source. Tongs with a long-handle or tweezers can be used to maintain the distance while handling RIs.

C) Protection through time measures

The radiation dose increases with the exposure time. Thus, the working time should be shortened by creating an experiment plan and by conducting sufficient preliminary experiments (cold run).

(2) Prevention of internal exposure

To prevent internal radiation exposure, one must take care of the three pathways—oral, airway, and skin. Although dependent on the chemical and physical properties, the following measures can be used to prevent radioisotopes from entering the body through these pathways. Rubber gloves should be worn to prevent RI from entering the body through the skin or wounds. RI should be handled inside a fume hood or draft chamber to prevent radiation from entering the body by inhalation. Safety bulb pipette fillers should be used to prevent accidental ingestion of RI reagents. In the controlled area, actions that risk accidental intake of radioisotopes should be avoided, such as eating, drinking, smoking, or applying makeup.

8 Handling of uranium, thorium, etc.

To ensure that nuclear material is used only for peaceful purposes and not for nuclear weapons, **it is necessary to designate a location to use/store several grams of nuclear material, accurately manage current inventory levels, and control its increase/decrease caused by the transfer in/out to the area over a set period.**

Nuclear fuel materials (materials that release high energy during nuclear fission such as uranium and thorium) and nuclear source materials (raw materials for uranium ore, thorium ore, and other nuclear fuel) are specified in the Atomic Energy Basic Act; thus, they are excluded from the RI Law. They are regulated by the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material, and Reactors, and it is necessary to obtain permission for their use. However, as shown in Table 8-6, permission is not required for the use of nuclear fuel materials in the range of types and within the quantities specified in Article 39 of the Order for Enforcement of the Act on the Regulation of Nuclear Source Material, Nuclear Fuel Material, and Reactors.

Table 8-6 Types and quantities of nuclear fuel material that do not require permission for use
(From the Nuclear Radiation Authority website)

	Type	Quantity permitted for use without further approval
(I)	Uranium and its compounds where the ratio of uranium-235 to uranium-238 is the natural mixing ratio.	Less than 300 grams of uranium
(II)	Uranium and its compounds where the ratio of uranium-235 to uranium-238 is below the natural mixing ratio.	Less than 300 grams of uranium
(III)	A substance containing more than 1-2 types of (I) and (II) and can be used as fuel in a nuclear reactor.	Less than 300 grams of uranium
(IV)	Thorium and thorium compounds.	Less than 900 grams of thorium
(V)	A substance containing more than 1-2 types of (IV) and can be used as fuel in a nuclear reactor.	Less than 900 grams of thorium

The following materials require usage approval regardless of quantity:

1. Uranium and its compounds where the isotopic ratio of uranium-235 to uranium-238 exceeds the natural abundance ratio
2. Plutonium and plutonium compounds
3. Uranium derived from Uranium-233 and its compounds

9 Equipment for Nuclear Safety Education at Nagaoka University of Technology and Examples of Experiments

The following equipment is stored at the Radioisotope Center at the Nagaoka University of Technology for nuclear safety education. The use of these devices provides an opportunity to acquire basic knowledge about radiation. Below, we list the equipment that can be used at the Nagaoka University of Technology, and in the next page we give examples of experiments that utilize the equipment.

- Basic scaler, Aloka (Hitachi), TDC-105, 1 unit
- GM tube, Aloka (Hitachi), GM-5004, 1 unit
- Measuring table, Aloka (Hitachi), PS-202, 1 unit
- β-chan, Chiyoda Technol Corporation, 5 units, includes lead, iron, and acrylic plates
- Scintillation survey meter, Aloka (Hitachi), TCS-171, 5 units, includes checking source (^{137}Cs)
- Lead blocks, PBBLOCK2B, 10 units, radiation shielding material
- Low-temperature diffusion cloud chamber, Shimadzu, WH-50, 1 unit, includes alpha ray source (^{241}Am)
- CCD camera for the low-temperature diffusion cloud chamber, 1 unit

A. Observe Invisible Radiation

Experiment objectives:

Radiation cannot be felt using the five senses. Hence, the objective is to observe the actual radiation emission through experiments using a cloud chamber.

Learning objectives:

Radiation is released radially from the radioactive source (Figure 8-8). Alpha rays have a short range and possess weak energy to penetrate matter. They can be shielded completely with paper, but they also pose a risk as they can pass all their energy to matter.

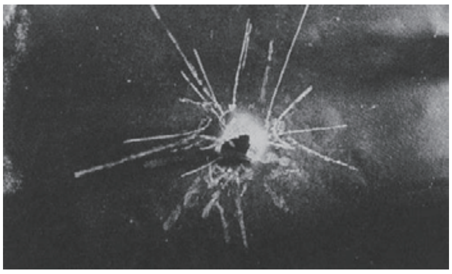

Figure 8-8 Flight path of alpha rays

Materials:

Low-temperature diffusion cloud chamber, ice, ice water container, ice water circulation pump and hose, ethanol (10 ml), pipette (1 unit), beaker (50 ml), paper cap (to shield α-radiation, handmade), CCD camera, camera support base (clamp or tripod), monitor (use from laboratories of each network), and camera-monitor connection cable.

Experimental Procedure: When using a low-temperature diffusion cloud chamber,

1. Set the low-temperature diffusion cloud chamber, CCD camera, monitor, ice water, and circulation pump.
2. Take out the alpha ray source for the cloud chamber to let students confirm that the radiation from the radiation emission slit is invisible.
3. Soak the felt in the cloud chamber with ethanol, attach the alpha ray source to the cloud chamber, and turn on the power for the cloud chamber and ice water circulation pump.
4. When radiation tracks can be seen in the cloud chamber window, set the CCD camera and monitor and let the students observe.
5. Explain the emission process and properties of the α-particle. Discuss the selection of the shielding material. Take out the alpha ray source from the cloud chamber.
6. Attach a paper cap to the tip of the alpha ray source and put it back in the cloud chamber.
7. After a while when radiation tracks can be seen in the cloud chamber window, let students observe that alpha rays can be shielded with paper, and discuss the experiment.

B. Radiation Safety Management

Experiment objectives:

Use a gamma radiation source (checking source) and scintillation survey meter to verify radiation shielding and changes in count number by distance, and learn safety management when handling radiation by applying protection measures of time, shielding, and distance.

Learning objectives:

Learn about the properties of the gamma radiation source (strong ability to penetrate matter) and selection of shielding material. Learn about the methods for the safe use of radioisotopes: the distance from the radiation source, shielding placed in the path of the radioisotope, and time spent handling the radiation source.

Materials:

Scintillation survey meter, checking source, and lead blocks.

Experimental Procedure:

1. Press the power button of the scintillation survey meter so that it is ready to take measurements.
2. Place the scintillation survey meter in a suitable location and record the measured values in the absence of a radiation source. Assume the time constant is 30 s. The value is best recorded after 90 s or more. Set this as the background value, A_{BKG}.
3. Next, measure the checking source. The net value obtained by subtracting A_{BKG} from the measured value becomes the value derived from the radiation source.
4. Verify the shielding effect of the lead block from the changes in measured value when the lead block is placed between the checking source and survey meter.
5. Confirm the effects of the distance from the radiation source through changes in measured value when the distance between the checking source and scintillation survey meter is extended to 2, 3, and 4 times. The experiment confirmed a relationship between the distance from the radioisotope and radiation exposure dose (the inverse square law), but did not observe proportional reduction as per the theory because a point source was not used.

C. Observation of background radiation

Experiment objectives:

Confirm that some substances existing in the natural world contain radioisotopes. Learn about the background radiation and its annual radiation dose.

Learning objectives:

Study the presence of background radiation and properties of beta rays (such as that from potassium fertilizer).

Materials:

Measurement experiment kit including β-chan

Experimental Procedure:

1. Check the power supply of the β-chan measuring device, and measure the radiation of each sample in the experiment kit (granite: 80–100 cpm; dried kelp: 100–120 cpm; potash (potassium chloride) fertilizer: approximately 10x background radiation; Potassium phosphoric acid fertilizer: lower than potash; geyserite: approximately 20x background radiation; crystal glass: 60–80 cpm)
2. Insert lead, iron, and acrylic plates between the measurement sample and β-chan to verify the shielding effects.
3. Increase the distance between the measurement sample and β-chan by 2, 3, and 4 times; verify the decrease in count number; and confirm the significance of taking distance measures for radiation safety.

In addition, other educational resources on nuclear safety are available, such as experiments on the half-life of radioisotopes and effects of shielding material thickness (Geiger/GM counter) and nuclide identification by radioisotope measurement and analysis (pulse-height spectrometry system).

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