8. Scientific and Industrial Applications

A key property of radionuclides which makes them invaluable is that they can be deteced in tiny amounts. It is claimed that George de Hevesy, a colleague of Rutherford and one of the pioneers of radioisotope tracers, first used a radioisotopes to test his food [1]. Hevesy lived in a boarding house and was suspicious that the stew his landlady was serving was made from the previous day leftovers. To test his hypothesis, he placed a small mount of radioisotope in his uneaten food. The following day, he examined the stew with a detector and established that some of the food had indeed come from the previous day leftovers. George de Hevesy won the Nobel Prize in Chemistry 1943 for his work on the use of isotopes as tracers in the study of chemical tracers.

Fig. 8.1. George de Hevesy (1885–1966). © The Nobel Foundation

In addition to nuclear power, there are the so-called "non-power" applications of radionuclides in areas such as medicine, agriculture, industry, environmental protection, public safety and space applications. These non-power applications of nuclear technology in the US alone generated sales in excess of \$ 300 billion and provided 4 million jobs (as of 1995). For comparison, nuclear power at the same time generated \$ 900 million in sales and provided 44 000 jobs [2]. In Japan, the economic value of non-power and power applications are about equal at \$ 50 billion per year. By far the largest contributor to non-power applications is in medicine. Here gamma rays are used on a very large scale to sterilise surgical dressings, structures, catheters, and syringes. In addition, more than 80% of all new drugs are tested with radioactive tagging before receiving government approval.

In the field of agriculture, pests reduce the world food production by 20–25% To reduce this, the sterile insects technique (SIT) is being used to control pest populations. Med flies have been eradicated in California, Chile, Argentina, and Peru. Tsetse and screwworm flies are also candidates for this treatment. Radiation is now used to enhance crop yields, provide improved nutrition, improve processing capabilities and disease resistance. Since the 1920s, radiation has been used to develop more than 2000 new crop varieties. In China, for example, more than one quarter of the crops for food produce is due to radiation.

Food irradiation is also receiving increased attention. With 76 million cases of food poisoning in the US each year, these numbers could be lowered by food irradiation before consumption. Recently, in the US, the supermarket chains have been introducing irradiated foods onto their shelves.

In industry, radiation is used in process controls for thickness gauges and density/level gauges (see below). For materials testing and inspection radiation is used to detect engine wear, check weld defects and corrosion in metals. For personal hygiene, radiation is used on contact lens solutions, bandages, cosmetics etc.

In space applications, NASA generates electricity from the radioactive decay of plutonium-238 for electricity and heating. The first space reactor, the SNAP-10A, was launched in April 1965 and functioned for 43 days before an electrical problem resulted in shutdown. The spacecraft, however, did indeed demonstrate that nuclear powered electrical sources were feasible. Recently there has been renewed interest in the use of nuclear propulsion to send a spacecraft to the moons of Jupiter (Project Prometheus). The so-called Jupiter Icy Moon Orbiter (JIMO) will orbit the three moons of Jupiter – Callisto, Ganymede, and Europa.

There is nowadays such a wide range of applications of radionuclides [3, 4, 5], that it is necessary to use some kind of classification system. In the following sections, the system used is based on the properties that make the radioisotopes useful. Following [1] these properties are:

1. Radiation traces Materials – Radioisotope Tracers
2. Materials affect Radiation – Radiography and Gauging
3. Radiation affects Materials – Radiation Processing
4. Radiation uses Energy – Nuclear Batteries

There are four main classes of application of radionuclides and radiation in industry: Radiosotope Tracers, Radiography and Gauging, Radiation Processing, Nuclear Batteries. Each of these will be described.

Radioisotope Tracers

The use of radionuclide tracers dates to the early days of radioactivity, when de Hevesy, a student of Rutherford, added the beta emitting nuclide ^{210}Pb to bulk lead to trace the solubility of lead salts. The use of so-called "tag" or "tracer" techniques using radionuclides is based on the fact that radiation can be detected with very high sensitivity. A very small number of "tagged" or "labelled" molecules added to a material allows one to monitor chemical and physical behaviour at both macro- and microscopic levels without disturbing the carrier material. Pesticides and insecticides, for example, are tagged using ^{14}C to monitor product degradation in the biosphere. In other areas of biochemistry, radioactive hydrogen (tritium) ^{3}H is used. Tiny amounts of about 10^{-15}g of the isotope ^{32}P are used implants to monitor the uptake of phosphorus in plants. A wide variety of radionuclide tracers are available for a variety of tasks. Some of these are outlined in more detail below.

Leak Detection

A common problem in the oil industry is the detection of leaks. For this purpose radionuclide tracers can be inserted into the pipe flow and will leak where the structure is damaged. If the pipe is not too deeply buried in the ground, the leak position can be identified from the gamma emission from the tracer radionuclide from above the soil.

Common Pipelines

Many pipelines carry oil from different producers at different times. To differentiate oil from from various producers, the oil soluble radionuclides can be used. Radiation monitors can then be used to identify different batches of oil.

Flow Patterns and Rates

By monitoring the diffusion of tagged radionuclide tracers, information on complex flows can be obtained [6]. This is particularly useful for studies on ocean currents, atmospheric pollution dispersion, sand movement on beaches, etc. For sand movement studies, for example, small glass beads are synthesised with particles sizes and densities matching those of the sand. The glass beads contain appropriate target material such as lanthanum oxide, iridium, or silver metal which is activated in a nuclear reactor to produce the radiotracers ^{140}La (1.7d), ^{192}Ir (74 d)), or ^{110m}Ag (250 d). The tracers are chosen such that their half-lives correspond to the timescale of interest (1 week, 1 season, annual cycle etc.). Radionuclides can also be used as tracers for flow rate measurement in complex systems such as in rivers.

Tracer Dilution

By injecting radionuclide tracers into unknown volumes of fluids, the volume of the fluid can be determined from the dilution of the tracer. If the unknown volume is V, then this is obtained from $V = V_0(C_0/C)$ where V_0 is the volume of tracer injected with concentration C_0 and C is the concentration in the unknown volume. This method can be used to determine, for example, the total amount of blood in a person's body, or the amount of catalyst in a chemical process etc.

Wear Analyses

A particularly important application of radionuclide tracers is in the study of wear, friction, corrosion, etc. The wear on piston rings in an engine, for example, can be analysed by tagging the rings with suitable radionuclides. By measuring the rate of appearance of the tag in the engine oil, the wear of the piston rings can be determined.

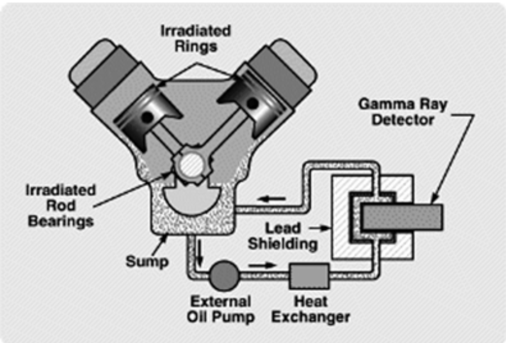


Fig. 8.2. A gamma ray detector, placed in the test engine's lubrication stream, detects and analyzes the presence of radioactive tracers emitted by abraded metal particles from irradiated engine parts [7]. © Southwest Research Institute

Mixing Times

An important problem in many industrial batch mixing processes is to ensure that the complete mixing occurs. By measuring the concentration of a tagged component at various times, the time required for mixing can be obtained.

Radiography and Gauging

The interaction of radiation with material generally results in a change in intensity or energy of the radiation. The penetration of radiation through a material depends on the density and thickness of the materials and the energy of the radiation. The resulting decrease in the intensity can be used as a basis for measuring thicknesses, finding voids, testing welds, detecting concealed objects, etc. The three main applications are *radiography*, *gauging* and *activation*.

X-Ray and Gamma Ray Radiography

One of the most spectacular applications of radiation was Roentgen's X-ray of his wife's hand in 1895. The image produced on a photographic plate placed beneath the hand showed clearly the underlying bones. Nowadays the technique of radiography is very well developed. X-rays of teeth and other parts of the body are now everyday procedures in practices and hospitals all over the world. In this technique, high energy electrons are directed on to a high-Z target material where they are slowed down thereby producing high energy photons or bremsstrahlung radiation. As these

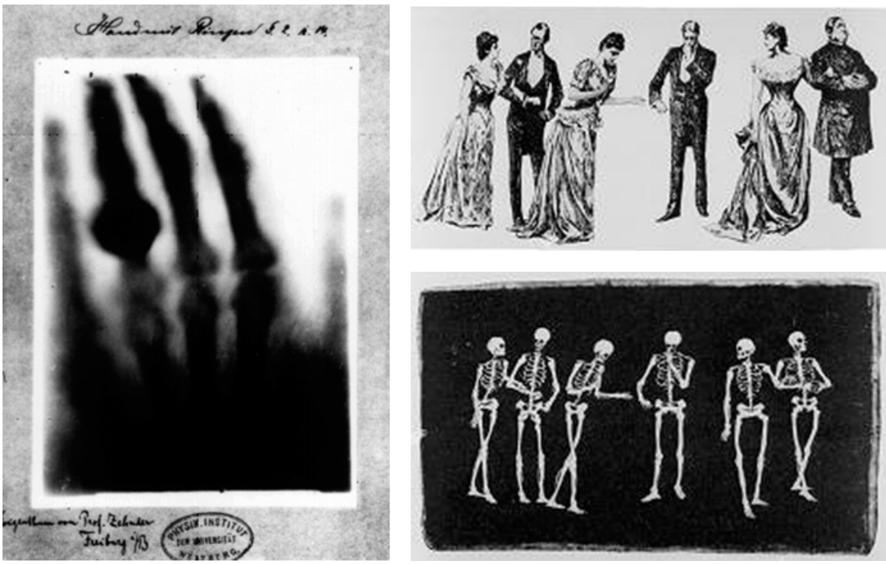


Fig. 8.3. (*Left*) The first X-ray picture: the radiograph of the hand of Roentgen's wife made by Roentgen on 22 Dec. 1895 [8], (*right*) Contemporary humour on X-rays in the magazine Life No. 27 of 6th April 1896, p. 313 [8]. © Deutsches Museum, Munich

high energy photons pass through tissue, dense objects absorb or scatter the photons preferentially resulting in less photons reaching the photographic plate. In situations where X-ray machines are impractical, the photon radiation can be obtained from radioisotopes. Such small scale radioisotope gamma sources are very reliable.

Neutron Radiography

Radioactive sources are too weak to produce images with the right quality. Neutron beam-lines from nuclear reactors or spallation sources [9] can also be used for radiography if the object has different neutron cross-sections. Because materials such as water and hydrocarbons are very effective at scattering thermal neutrons, in contrast to gases, voids, metals etc., neutron radiographs are ideal for analysing the density variations in neutron absorbing and scattering materials.

Most of the existing neutron radiography facilities are reactor-based. At the Paul Scherrer Institute (PSI) in Switzerland [9], however, the neutrons are produced in the SINQ spallation source. Neutron radiography stations are almost exclusively large stationary installations. This makes them unsuitable for “in situ” measurements.

Since X-rays interact with atomic electrons, the interaction probability is greatest with high atomic number Z as shown in Fig. 8.4. Neutrons have no electric charge and interact only with the atomic nucleus. Neutron interactions do not vary systematically with Z as do X-rays – however certain low Z materials (such as hydrogen, boron) show strong interaction probabilities.

A neutron transmission radiography setup, Fig. 8.5, consists of a neutron source, a collimatior to guide the neutons to the sample and an neutron detector to collect the transmitted neutrons behind the sample.

Thermal neutron fluxes in the range 10^5–10^7 cm^{-2} s^{-1} are used in neutron radiography. Exposure times for the detection of neutrons and X-rays are only a few seconds. Thermal neutrons are preferrred due to their hight interactions probability with the observed materials, but also with the detection materials (^{11}B, ^{6}Li, ^{155,157}Gd). The most important detections reactions are (for thermal and cold neutrons) [9]:

$$^3\mathrm{He} + {}^1\mathrm{n} \rightarrow {}^3\mathrm{H} + {}^1\mathrm{p} + 0.77\,\mathrm{MeV}$$

$$^6\mathrm{Li} + {}^1\mathrm{n} \rightarrow {}^3\mathrm{H} + {}^4\mathrm{He} + 4.79\,\mathrm{MeV}$$

$$^{10}\mathrm{B} + {}^1\mathrm{n} \xrightarrow{(7\%)} {}^7\mathrm{Li} + {}^4\mathrm{He} + 2.78\,\mathrm{MeV}$$

$$^{10}\mathrm{B} + {}^1\mathrm{n} \xrightarrow{(93\%)} {}^7\mathrm{Li}^* + {}^4\mathrm{He} + 2.30\,\mathrm{MeV} \rightarrow {}^7\mathrm{Li} + {}^4\mathrm{He} + \gamma\,(0.48\,\mathrm{MeV})$$

$$^{155}\mathrm{Gd} + {}^1\mathrm{n} \rightarrow {}^{156}\mathrm{Gd} + \gamma + \text{conversion electrons } (7.9\,\mathrm{MeV})$$

$$^{157}\mathrm{Gd} + {}^1\mathrm{n} \rightarrow {}^{158}\mathrm{Gd} + \gamma + \text{conversion electrons } (8.5\,\mathrm{MeV})$$

X-ray and neutron transmission images look different and provide complimentary information. In the camera images shown in Fig. 8.6, the metallic parts are revelaed clearly in the X-ray images, whereas plastic components are shown clearly with the neutrom images.

The neutron radiography facility at the Paul Scherrer Institute (PSI) in Switzerland – the Neutron Transmission Radiography NEUTRA (NEUtron Transmission

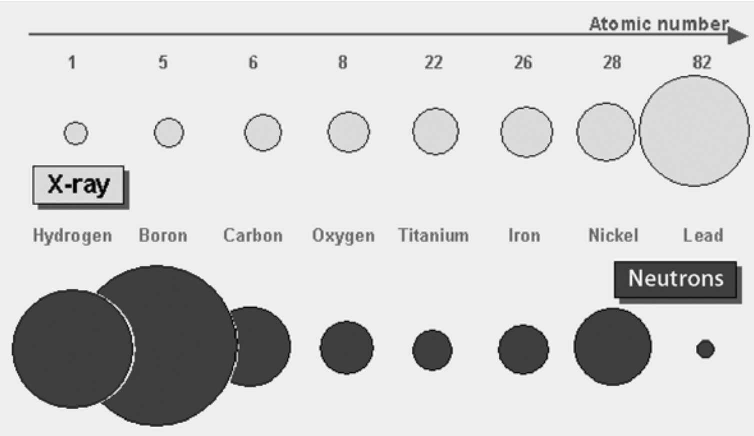


Fig. 8.4. Neutron matter interaction probability: comparsion between neutrons an X-ray. Circles with larger diameters have higher interaction probabilities or cross-sections [9]

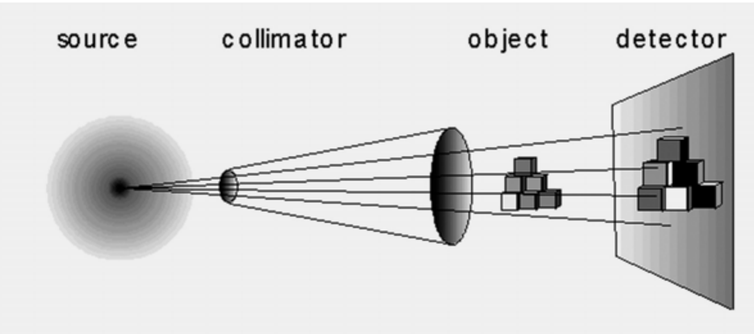


Fig. 8.5. Principle of neutron radiography [9]

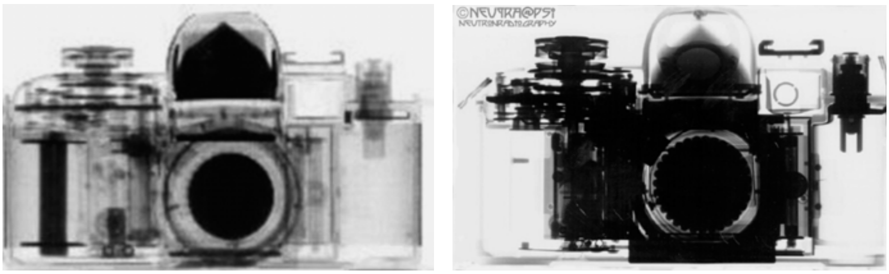
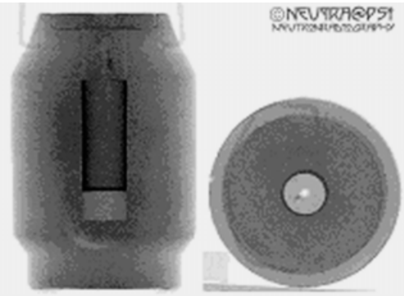


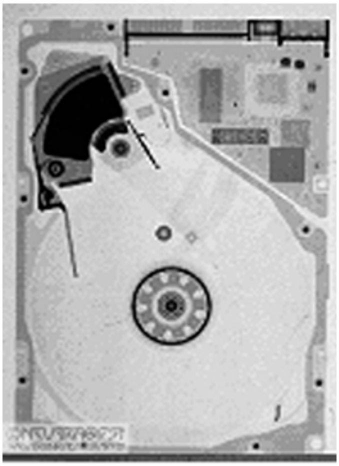
Fig. 8.6. Unlike X-rays, neutrons interact significantly with some light materials and penetrate easily some heavy materials, making it a complementary technique to X-ray radiography. While X-rays are attenuated more effectively by heavier materials like metals, neutrons make it possible to image some light materials such as hydrogenous substances with high contrast: in the X-ray image (left), the metal parts of the photo apparatus are seen clearly, while the neutron radiograph (right) shows details of the plastic parts [9]

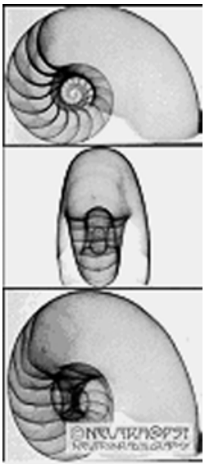
RAdiography) – station has been in operation at the spallation source SINQ since 1997. The aim of NEUTRA is to provide a state-of-the-art tool for scientific and industrial neutron radiography applications. Typical applications of neutron radiography are shown in Fig. 8.7.



(**b**) Uranium can be transmitted by thermal neutrons and the enrichment of the isotope U-235 can be measured (and visualized) due to the higher attenuation compared to U-238. The "black" areas in the image are pellets with the "burnable poison" Gadolinium.

(**a**) Neutrons can penetrate lead provided it is not too thick. The container shown contained possibly dangerous material. By neutron inspection it was verified easily that it is empty and only a plastic cylinder was inside.





(**c**) Hard-disks are electro-mechanical devices which are sealed and cannot easily be opened for inspection. Non-invasive investigation can help to evaluate the status of enclosed componenets with a high resolution.

(**d**) The wooden puppet (very popular Russian "Matroschka") contains several "daughters".

(**e**) The very interesting inner structure of the (empty) shell of a Nautilus scrobiculatus can be visualised by neutrons due to the relative high contrast of the shell material. The size of this object is about 20 cm.

Fig. 8.7a–e. Various applications of neutron radiography. © NEUTRA@PSI

Level Gauging

Properties of the material can be determined from changes in the radiation using "gauges" (or nucleonic gauges) consisting of a radioactive source and a detector such as a NaI crystal. In many industrial processes there is a need to determine the level of a liquid in a container. A simple gauge consists of a source of radiation and a detector with a line of axis near the surface (either above or below) of the liquid. If the surface level of the liquid moves, the detector signal changes accordingly. In the drinks industry, this technique is used to ensure that cans on high-speed conveyor belts are properly filled.

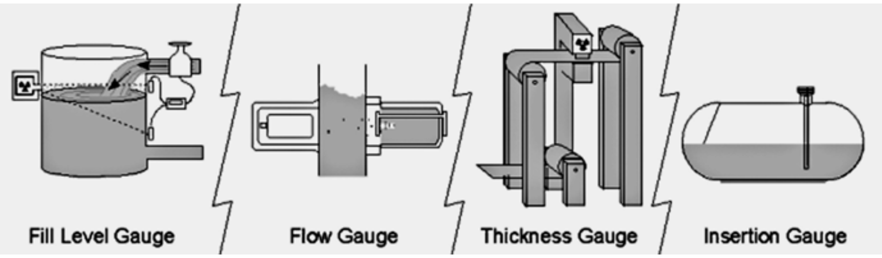


Fig. 8.8. Examples of several different types of fixed gauges [10]

Thickness Gauging

Thickness gauging is used in processes involving continuous sheets of materials such as adhesive tape, floor coverings, paper production etc. The thickness of the material is determined from the measurement of the transmitted or reflected radiation.

Density Gauging

Density gauges are used to measure the density of material between the source and detector based on the radiation attenuation in the material. The basic relation used is

$$I_t = I_0 \mathrm{e}^{-\mu_\mathrm{m} \rho t}$$

where I_0 and I_t are the gamma ray intensities before and after attenuation through a material of thickness t, ρ is the density of the material and μ_m is the mass attenuation coefficient.

Neutron Activation Analysis

Neutron activation analysis is used to detect very small amounts of impurities or trace elements in a sample. Small samples undergo neutron irradiation whereby the neutrons activate the stable atoms to radioactive atoms. Following the irradiation, the sample is analysed using gamma spectroscopy to identify the emission and thus determine the origin of the radiation. The technique is widely used in nuclear forensic science to obtain a "fingerprint" of the material. The technique has potential applications for example to plastic explosive detection at airports or detecting buried landmines.

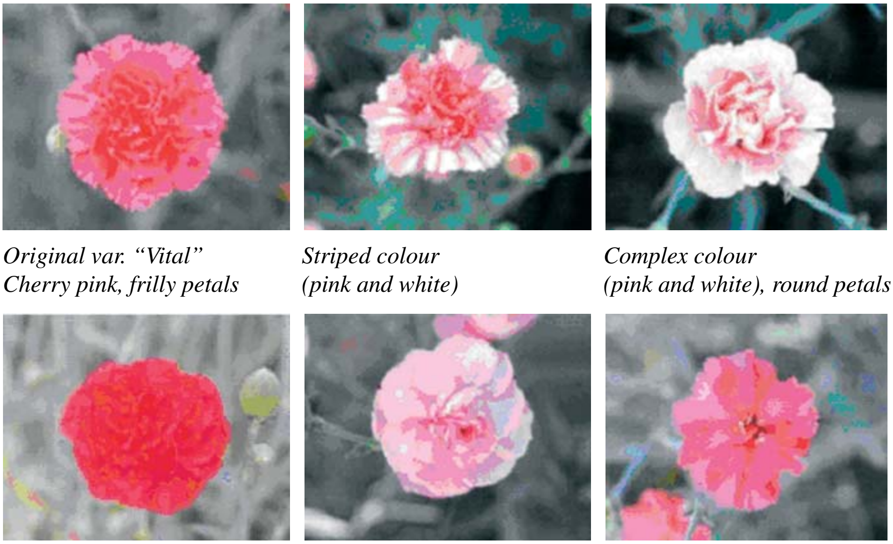
Fig. 8.9. Gamma radiography of the gold mask of Tutankhamon made for the Exhibition "Toutankhamon et son Temps", Paris 1967. © Rights reserved

Radiation Processing

In the same way that overexposure to sunlight can lead to sunburn, overexposure to radiation from radioisotopes can result in cell damage. At lower dose levels, radiation induced mutation of DNA cells can occur. At sufficiently high dose levels, radiation can be used to kill bacteria and insects. This is the basis of using radiation for sterilisations of materials and foods. In the following section, processes are described in which radiation is used to modify the properties of materials. In specific cases, because large volumes requiring treatment, very large doses of radiation may be required.

Radiation-Induced Mutation

Through the process of stochastic mutation of DNA cells by radiation, plants exhibiting desired features can be selected. As a result new genetic lines of, for example, garlic, wheat, bananas, beans, avocado and peppers can be produced which are more resistant to pests and climate. Using the technique of radiation-induced mutation, the shape, size and colour of flowers can be changed (see Fig. 8.10). Recently bioluminescent flowers have been developed by genetic modification using a gene from fireflies. These flowers produce constant light, visible to the human eye, for up to five hours. The bioluminescent plants use their own energy to create light, and radiate a greenish-white glow from all parts of the orchid, including roots, stem, leaves and petals.



Original var. "Vital"
Cherry pink, frilly petals

Striped colour
(pink and white)

Complex colour
(pink and white), round petals

Red colour, round petals

Pink colour, round petals

Dianthus type petals

Fig. 8.10. Mutant carnation flowers. Irradiation with carbon ions resulted in various changes on both flower colour and shape. From the original variety "Vital" (*left top*), flowers with stripes, bi-colour/round shape, red/round shape, pink/round shape, and Dianthus type shape were obtained [11]

Food Irradiation

Radiation can be used to reduce the high losses of food due to insect infestation and spoilage, reduce concern over food-borne illness and help to increase international trade in food products. At present over 30 countries have permission to irradiate around 40 different foodstuffs ranging from fruits and vegetables to seafood, meat and poultry. An advantage of radiation processing of food over thermal pasteurisation processes is that the former does not change the flavour of the food product. Typical gamma or X-ray doses required are in the range of kGy to hundreds of Gy (Fig. 8.11).

Sterilisation

Radiation sterilising is based on the use of gamma rays and accelerated electrons to destroy bacteria, fungi and viruses. It works through the sealed packaging of the material, without raising the temperature or requiring the addition of any chemical. It is particularly of interest for medical supplies many of which cannot withstand high temperatures (e.g. plastic syringes). Recently it has been proposed to destroy anthrax bacterium sent in mail by the use of such radiation.

Insect Control

Insect control using radiation consists of irradiating laboratory male insects before hatching, to sterilise them. The sterilised males are then released to the environment

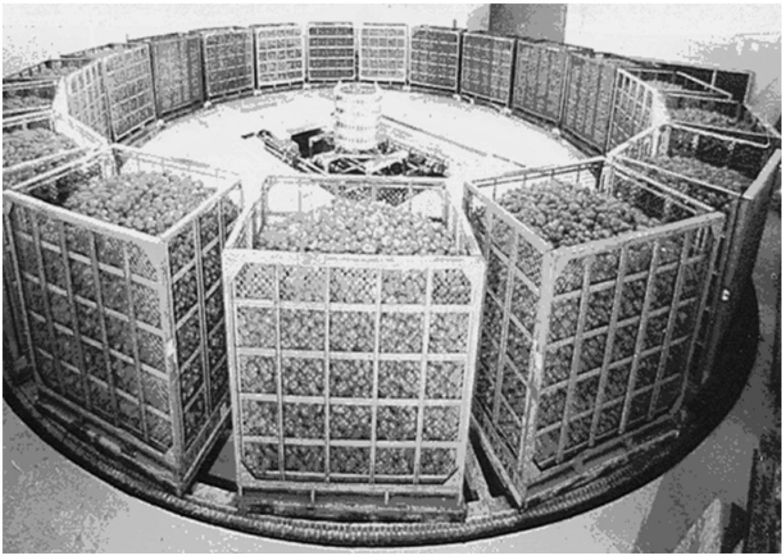


Fig. 8.11. Shihoro Potato irradiation facility located in Hokkaido, Japan [12]. In Japan 10,000 tons of potatoes are irradiated per year to inhibit sprouting

in the infested areas. Following mating with females, no offspring are produced. Repeated releases of sterilised males in the affected area will result in almost complete elimination of the insect pest. Successful operations have been carried out in Mexico against the Medfly (Mediterranean fruit fly) and the screwworm.

Nuclear Batteries

Using the energy released from the radioactive decay of radionuclides for the purpose of heating, lighting, or electricity production is an attractive concept. Devices using such energy sources could operate for long periods without human intervention. One problem, however, is that that relativley large quantities of radioactive materials are required to generate powers in excess of a few watts. One of the SNAP thermoelectric generators with an output power of 68 W contained 2.25×10^5 Ci of ^{90}Sr. Another problem is that such large amounts of radioactive material is a considerable health hazard.

Conversion of Radioactive Decay Energy to Electricity

There are basically two ways to convert radioactive decay energy to electricity:

1. The decay energy is converted to thermal energy which is then further converted to electrical energy.
2. The emitted radiation (charged particle or photon) is converted directly to electrical energy

In the first case, electrical energy generation is based on a thermal cycle using radionuclide heat sources (RHSs). Although there are many methods for the conversion, the most suitable for RHSs are the dynamic, thermionic, and thermoelectric methods [13]. In the *dynamic* method, the generator is driven by a circulating fluid in a closed system which is evaporated by the radionuclide source. The conversion efficiency of such systems is typically 10–15%.

In the *thermionic* method, heat from the source is used to generate electrons via thermoelectric emission. The efficiency is around 20%. The most practical method for thermoelectric conversion, however, is the *thermoelectric* method first proposed by Ioffe in 1929. In this method thermal energy is converted to electrical energy based on the thermo-electromotive force arising from a temperature gradient between two sides of an electrical circuit consisting of different conductors or semiconductors. The hot junctions are in thermal contact with the source. The cold junctions are cooled by heat removal. The maximum efficiency is around 6%.

In the second case, electrical energy is produced directly via direct charge, direct conversion, or indirect conversion methods. In the *direct charge battery*, the charge particles are collected directly onto a battery electrode. These give rise to typically large voltage low current systems. The first battery based on this idea was suggested by Mosely in 1913. A thin walled spherical quartz ampule filled with radium was used as the emitter. The alpha particles were retained by the walls and the beta particles were transmitted through the walls. An electrode was used to collect the beta particles. These direct charge batteries produce high voltage (10–100 kV) and deliver powers in the range micro-milliwatt at high efficiency (typically 75%). In *direct conversion batteries*, the radiation (alpha, beta etc.) is used to ionise a gas filling the space between two metal electrodes with different work functions. The electrodes contact potential difference creates the electric field for the charged particles. The energy conversion in these systems, however, is only around 0.5% due to the high energy required for ion pair formation (around 30 eV).

In indirect conversion batteries, the energy released by the radioactive decay is transformed to light radiation using radioluminescent methods. The light energy is later converted to electrical energy by photovoltaic methods.

Nuclear Batteries Based on Beta-Emitters

Beta-emitters with stable daughters are the least hazardous sources since they can shielded relatively easily – even in significant amounts. These are suitable for light or electricity production but not for heat production since not much heat is generated (typically beta energies are 200–300 keV). As energy sources, the half-lives of the isotopes should be a few years. From the more than 3000 known radionuclides, only a few are beta emitters with stable daughters and suitable half-lives such as ^{3}H, ^{14}C, ^{45}Ca, and ^{63}Ni. Other nuclides of interest are ^{55}Fe (Auger electron emitter), ^{147}Pm (with soft gammas) and ^{204}Tl (high energy beta). Some of their characteristics are listed in Table 8.1.

The specific power, P_{sp}, per Curie of activity is defined as

$$P_{\mathrm{sp}} = 3.7 \times 10^{10} \cdot \int_{0}^{\varepsilon_{\max}} w(\varepsilon_\beta) \cdot \varepsilon_\beta \cdot \mathrm{d}\varepsilon_\beta = 3.7 \times 10^{10} \cdot \varepsilon_{\mathrm{av}}$$

Table 8.1. Characteristics of radionuclides of interest as energy sources [13]

Nuclide	^{3}H	^{14}C	^{45}Ca	^{55}Fe	^{63}Ni	^{147}Pm	^{204}Tl
Halflife y	12.3	5710	0.44	2.7	100	2.7	3.8
Radiation	β^-	β^-	β^-	e^-, X	β^-	β^-, weak γ	β^-, X
Average energy, keV	5.7	49	77	e^--5.2	17.6	62	243
P_{sp}, μW Ci^{-1}	34	290	456	e^--18, X-10	100	367	1440

where ε_β is the kinetic energy of the beta particle, $w(\varepsilon_\beta)$ is the distribution function and ε_{av} is the average energy. When the ε_{av} is measured in keV, and P_{sp} in μW Ci^{-1} then

$$P_{sp} = 5.92\,\varepsilon_{av}\,.$$

Tritium is of special interest for light generation. From Table 8.1, the average beta energy is 5.7 keV implying a maximum beta energy of (3 × average) approximately 18 keV. This is also the energy of the electrons in cathode ray tubes in televison sets. The paths length for electrons in solids with this energy is only a few microns implying that heavy shielding is not required. Tritium is used in many different forms for radioluminescent light sources e.g. metal tritides, tritium loaded silicon, tritium containing zeolites and aerogels, selected organic tritium containing compounds.

Nuclear Batteries for Microelctromechanical Systems (MEMS)

Using microelectromechanical systems (MEMS) technology, also known as nanotechnology or micromechanics, tiny devices can be produced which can perform precise functions in applications such as medical equipment, environmental management, and in automobiles. A common application for MEMS is as tiny sensors in airbags in cars [14].

One possibility to power these tiny systems is with nuclear batteries. A fundamental advantage of power units based on radionuclides lies in their power density and longevity [15]. In Table 8.2 a list of potential candidate nuclides for such applications is shown. The data is taken from the Nuclides.net database. The heat generation resulting from radioactive decay is also shown. A characteristic of these MEMS is that they require power sources that are both lightweight and intense.

Normally, exposure to radioactive materials is hazardous and their use must be closely regulated. However the amounts of materials required (to produce power in the range of nanowatts to microwatts (nW-μW) is so small that they may not pose safety risks or require regulation. In addition these radioactive energy sources would be encapsulated to withhold the radiation.

Table 8.2. Potential candidate nuclides for nuclear powered MEMS [15]

Nuclide	Half-life	Isotopic power	Quality	Energy
^{3}H	12.3 y	300 W g^{-1}	Low energy β^-, no gammas	18.57 keV (β^-)
^{14}C	5730 y	1.3 mW g^{-1}	Low energy β^-, no gammas	156.5 keV (β^-)
^{32}Si	132 y	34.5 mW g^{-1}	Low energy β^-, no gammas	225 keV (β^-)
^{63}Ni	100.1 y	5.7 mW g^{-1}	Low energy β^-, no gammas	65.87 keV (β^-)
^{90}Sr	28.84 y	160 mW g^{-1}	Low energy β^-, no gammas	546 keV (β^-)
^{121}Sn	1.13 d	642 W g^{-1}	Low energy β^-, no gammas	383 keV (β^-)
^{134}Cs	2.06 y	1.32 W g^{-1}	β^-, and gamma emission	Range (β^-, γ)
^{147}Pm	2.62 y	340 mW g^{-1}	Low energy β^-, no gammas	224.5 keV (β^-)
^{151}Sm	90 y	4 mW g^{-1}	β^-, and gamma emission	76.3 keV (β^-), 21.5 keV (γ)
^{204}Tl	3.78 y	3.4 mW g^{-1}	β^-, low energy gammas	349 keV (β^-)
^{210}Po	138.4 d	144 W g^{-1}	High energy α, low energy γ	5.3 MeV (α, γ)
^{228}Ra	5.75 y	38 mW g^{-1}	β^-, low energy gammas	39 keV (β^-)
^{241}Am	432.2 y	115 mW g^{-1}	High energy α, low energy γ	Range (α, γ)
^{242}Cm	162.8 d	122 W g^{-1}	High energy α, low energy γ	Range (α, γ)
^{244}Cm	18.1 y	2.8 W g^{-1}	High energy α, low energy γ	Range (α, γ)