CHAPTER 7

Non-Power Use of Nuclear Energy

Contents

7.1 NON-POWER APPLICATIONS

Nuclear energy is an important source of CO_2-free baseload electricity providing an excellent alliance with renewables which need underpinning baseload for when the wind does not blow or the sun shine. However, nuclear applications are not just limited to power generation. The non-power uses of nuclear energy include many useful applications in science, medicine, industry, food preservation and agriculture. Applications use either radiations such as in accelerators and gamma irradiators or a combination of chemical properties and radiations emitted by radionuclides such as in radioactive tracers and radiopharmaceuticals (Tsoulfanidis, 2018). During the use of nuclear energy radioactive waste can be generated, which must be managed with particular care owing to its inherent radiological, biological, chemical and physical hazards. Producers and users of radioactive materials must be sure that a waste management strategy exists prior to the start of waste generation (IAEA, 2017a).

7.2 SCIENTIFIC APPLICATIONS

Geology, *paleoethology* and *archaeology* benefit from using radionuclides of primordial or cosmogenic origin in dating geological formations, minerals, rocks, fossil specimens and ancient artefacts. The age of a certain specimen is known from the contents of accumulated and remnant radionuclides

An Introduction to Nuclear Waste Immobilisation
DOI: https://doi.org/10.1016/B978-0-08-102702-8.00007-8

such as ^{40}Ar and ^{40}K, ^{206}Pb and ^{238}U, or ^{12}C and ^{14}C (see Sections 4.3 and 4.5).

Well logging in geological surveys characterises geologic formations through boreholes using natural radioactivity measurement and neutron and gamma rays. It involves neutron and gamma ray sources and radiation detectors which are lowered into boreholes. The epithermal neutrons typically used are losing energy through elastic scattering to near-thermal levels before being absorbed by the nuclei in the rock formation. Gamma rays and neutrons resulting from scattering and capture are detected, giving information on porosity and composition. Nuclear well logging helps assess the commercial viability of new or existing wells in oil and gas exploration.

Density of materials can be found using nuclear density gauges, which apply neutron and gamma radiations measuring the reflected (scattered) component that depends both on density and composition. Density gauges are often used in construction of roads to determine the density and moisture content of soils, asphalt, and concrete.

Physical and *chemical* research uses various aspects of nuclear energy. Neutron activation analysis is often used to quantify unknown compositions. Samples of unknown substances are bombarded with neutrons using either nuclear reactors or *neutron generators* producing neutrons from deuterium−deuterium (D−D) or deuterium−tritium (D−T) nuclei fusion. D−D fusion results in the formation of a ^{3}He particle and 2.5 MeV neutrons whereas D−T fusion reaction generates ^{4}He and 14.1 MeV neutrons. The nuclei of samples absorb neutrons with many resulting nuclei being radioactive. The activity induced A_c is found as:

$$A_c = N \sigma \phi [1 - \exp(-\lambda t)], \tag{7.1}$$

where N is the number of nuclei in the sample, σ is the neutron absorption cross-section, ϕ is the neutron flux. The emissions resulting from the decay of radioactive nuclei formed are measured determining the spectra of emissions and so through their analysis the parent nuclei are identified.

Flow tracing aiming to analyse pollutant flow and movement of underground and surface waters, measure water runoff, determine leaks, flow rates, dilution and mixing rates is done by adding a radioactive tracer to a gas or liquid.

Radionuclides are used to study metabolic, toxicological or environmental pathways associated with a range of compounds such as drugs, pesticides, fertilisers and minerals. Work may be related to areas such as the manufacture of new drugs, crop production and environmental studies. The radionuclides most commonly employed in studying the toxicology of many chemical compounds and their associated metabolic pathways are ^{14}C and ^{3}H, as they can be readily incorporated into complex molecules, while ^{33}P is widely used as a tracer in genetics (IAEA, 2005).

Friction wear is found by impregnating a tracer in the body of working material and detecting the component when released. High temperature measurements for refractory materials such as those operating as internals of jet engines or turbine blades can be done using radioactive noble gases such as ^{85}Kr impregnated in the material.

7.3 MEDICAL AND BIOLOGICAL APPLICATIONS

Biological and *medical* research uses radiations and radionuclides because chemically they have a similar behaviour as non-radioactive nuclides. *Medicine* uses radiations such as X- and gamma-rays and radionuclides for diagnosis and treatment of diseases.

Diagnosis includes X-ray imaging such as chest X-ray imaging to detect diseases such as pneumonia, pneumothorax, interstitial lung disease, heart failure, bone fractures and others. Dental X-ray radiography is used in the diagnosis of dental structures, finding healthy and malignant parts that need treatment.

Positron emission tomography (PET) is a technique that detects pairs of gamma rays emitted indirectly by a positron-emitting radionuclide such as ^{15}F, ^{15}O, ^{11}C which is introduced into the patient body on a biologically active molecule. The distribution of radionuclide concentration within the body is constructed by computer based on detected signals in the form of 3D images. PET is used to diagnose diseases and to analyse metabolic processes in the body.

Radiopharmaceuticals are used for clinical diagnosis, therapy and medical research. Commercially available kits contain typically kBq quantities of radionuclides that are used for *in vitro* radioassay with ^{125}I as the main radionuclide (IAEA, 2005). Imaging of organs is typically done using ^{99m}Tc as the most common radionuclide ($T_{1/2}$ = 6 hours), which is normally eluted in a sterile environment from a commercially supplied generator containing ^{99}Mo ($T_{1/2}$ = 66 hours). Table 7.1 gives data on typical use of radiopharmaceuticals for injection, ingestion or inhalation (Tsoulfanidis, 2018). Table 7.2 gives data on the most frequently used radionuclides in medicine and biological research (IAEA, 2005).

Table 7.1 Typical uses of radiopharmaceuticals for imaging or therapy

Radionuclide	Chemical form	Organ
^{32}P	Chromic phosphate, sodium phosphate	Pleura, peritoneum, bone
^{51}Cr	Albumin, sodium chromate	Spleen
^{99m}Tc	Sodium pertechnetate	Most systems
^{111}In	Indium pentetate, autologous leucocytes, OncoScynt	Brain surface or spleen
^{125}I	Sodium iodide, albumin, fibrinogen, iothalamate	Thyroid and ovaries
^{131}I	Orthoiodohippurate, sodium iodide	Bladder wall and thyroid
^{133}Xe	Gas	Lung
^{201}Tl	Thallous chloride	Myocardial

Radiotherapy treats diseases by using nuclear energy to kill malignant cells, irradiating them with suitable radiations. Two main types of radiotherapy are used – teletherapy and brachytherapy. *Teletherapy* uses intensive sources of radiation such as gamma rays provided by ^{60}Co, ^{192}Ir and ^{137}Cs sources or accelerators with beams of radiation focused on tumours and provision ensured to shield healthy tissue. *Brachytherapy* uses direct contact of small capsules with radionuclides – sealed radioactive sources – surgically implanted in the tumours. Radionuclides such as ^{131}I, ^{32}P, ^{90}Y and ^{89}Sr are administered to patients for therapeutic purposes in activities ranging from 200 MBq to 11 GBq. Table 7.3 gives typical data on sealed radioactive sources used in radiotherapy (IAEA, 2005).

7.4 INDUSTRIAL APPLICATIONS

Nuclear energy is used for various industrial applications, such as for seawater desalination, hydrogen production, district heating or cooling, extraction of tertiary oil resources and process heat applications such as cogeneration, coal-to-liquids conversion and assistance in the synthesis of chemical feedstock (IAEA, 2017b). Sealed radioactive sources are used extensively in industry for non-destructive testing such as radiography and gauging.

Radiography is used to analyse the inside of solid products, placing them between the source and a photographic film or imaging detector.

Thickness gauges and level indicators are widely used, measuring the intensity of radiation passing through the material and enabling a

Table 7.2 Radionuclides used in medicine and biological research

Radionuclide	Half-life[1]	Typical activity	Application
^{3}H	12.3 y	≤ 50 GBq	Radiolabelling, biological research, organic synthesis
^{11}C	20.4 m	≤ 2 GBq	PET, lung ventilation studies
^{14}C	5730 y	<1 MBq	Medical diagnosis
		≤ 50 GBq	Biological research
		≤ 50 GBq	Labelling
^{15}O	122 s	≤ 2 GBq	PET, lung ventilation studies
^{18}F	1.8 h	≤ 500 MBq	PET
^{24}Na	15 h	≤ 5 GBq	Biological research
^{32}P	14.3 d	≤ 200 MBq	Therapeutic nuclear medicine
^{33}P	25.4 d	≤ 50 MBq	Biological research
^{35}S	87.4 d	≤ 5 GBq	Medical and biological research
^{36}Cl	3.01×10^{5} y	≤ 5 MBq	Biological research
^{45}Ca	163 d	≤ 100 MBq	Biological research
^{46}Sc	83.8 d	≤ 500 MBq	Medical and biological research
^{51}Cr	27.7 d	≤ 5 MBq	Diagnostic nuclear medicine
		≤ 100 MBq	Biological research
^{57}Co	271.7 d	≤ 50 MBq	Diagnostic nuclear medicine
^{58}Co	70.8 d	?	Biological research
^{59}Fe	44.5 d	≤ 50 MBq	Diagnostic nuclear medicine, biological research
^{67}Ga	3.3 d	≤ 200 MBq	Diagnostic nuclear medicine
^{68}Ga	68.2 m	≤ 2 GBq	PET
^{75}Se	120 d	≤ 10 MBq	Diagnostic nuclear medicine
^{81m}Kr	13.3 s	≤ 6 GBq	Lung ventilation studies
^{85}Sr	64.8 d	≤ 50 MBq	Biological research
^{86}Rb	18.7 d	≤ 50 MBq	Medical and biological research
^{82m}Rb	6.2 d	≤ 50 MBq	Diagnostic nuclear medicine
^{89}Sr	50.5 d	≤ 300 MBq	Therapeutic nuclear medicine
^{90}Y	2.7 d	≤ 300 MBq	Therapeutic nuclear medicine, medical and biological research
^{95}Nb	35 d	≤ 50 MBq	Medical and biological research
^{99m}Tc	6 h	≤ 100 GBq	Diagnostic nuclear medicine, biological research
^{111}In	2.8 d	≤ 50 MBq	Clinical measurements, biological research
^{123}I	13.2 d	≤ 500 MBq	Medical and biological research
^{125}I	60.1 d	≤ 500 MBq	Diagnostic nuclear medicine
^{131}I	8 d	≤ 11 GBq	Therapeutic nuclear medicine
^{113}Sn	155 d	≤ 50 GBq	Medical and biological research

(*Continued*)

Table 7.2 (Continued)

Radionuclide	Half-life[1]	Typical activity	Application
^{133}Xe	5.3 d	≤ 400 MBq	Diagnostic nuclear medicine
^{153}Sm	1.9 d	≤ 8 GBq	Therapeutic nuclear medicine
^{169}Eu	9.3 d	≤ 500 MBq	Therapeutic nuclear medicine, diagnostic nuclear medicine
^{198}Au	2.7 d	≤ 500 MBq	Therapeutic nuclear medicine, diagnostic nuclear medicine
^{201}Tl	3 d	≤ 200 MBq	Diagnostic nuclear medicine
^{203}Hg	46.6 d	≤ 5 MBq	Biological research

PET, Positron emission tomography.
[1]y = years, d = days, s = seconds, h = hour, m = minutes

Table 7.3 Sealed radioactive sources used in medicine

Radionuclide	Half-life[1]	Typical activity	Application
^{241}Am	433 y	1–10 GBq	Bone densitometry
^{153}Gd	244 d	1–40 GBq	
^{125}I	60.1 d	1–10 GBq	
^{239}Pu-Be	2.41×10^4 y	?	
^{198}Au	2.7 d	50–500 MBq	Manual brachytherapy
^{137}Cs	30.17 y	30–300 MBq	
^{226}Ra	1600 y	50–500 MBq	
^{32}P	14.3 d	?	
^{60}Co	5.3 y	50–1500 MBq	
^{90}Sr	29.1 y	50–1500 MBq	
^{103}Pd	17 y	50–1500 MBq	
^{125}I	60.1 d	200–1500 MBq	
^{192}Ir	74 d	?	
^{106}Ru	1.01 y	?	
^{137}Cs	30.17 y	?	Remote after-loading brachytherapy
^{192}Ir	74 d	200 TBq	
^{60}Co	5.3 y	50–1000 TBq	Teletherapy
^{137}Cs	30.17 y	500 TBq	
^{60}Co	5.3 y	50–1000 TBq	Whole blood irradiation
^{137}Cs	30.17 y	2–100 TBq	

Pacemakers used to generate electrical impulses control heart muscles and regulate the electrical conduction system of the heart can be powered by small nuclear batteries (IAEA, 2014).
[1]y = years, d = days, s = seconds, h = hour

continuous control of such parameters as thickness, density, level of liquids or grainy materials.

Radionuclides such as ^{241}Am or ^{210}Po are used to remove electric charges on the material and to avoid the build-up of static electricity in production of paper, plastics and synthetic textiles.

Powerful sealed radioactive sources are used for sterilisation of tools and equipment, and sterilisation of food and other products. Sealed sources are also used for process control and for the calibration of laboratory equipment. The dominant radionuclide is present in a very concentrated form with the total activity depending on the application (see Table 7.4; IAEA, 2005).

Table 7.4 Sealed radioactive sources used in industry (IAEA, 2005)

Radionuclide	Half-life[1]	Typical activity	Application
^{22}Na	2.6 y	?	Thickness gauges
^{55}Fe	2.6 y	≤ 5 GBq	Density gauges
^{85}Kr	10.7 y	≤ 100 GBq	Well logging
^{90}Sr	28.1 y	≤ 10 GBq	Moisture detectors
^{109}Cd	1.27 y	?	X-ray fluorescence
^{134}Cs	2.1 y	≤ 20 GBq	
^{137}Cs	30.17 y	≤ 10 GBq	
^{147}Pm	2.62 y	≤ 2 GBq	
^{241}Am-Be	433 y	≤ 500 GBq	
^{238}Pu	87.7 y	≤ 5 GBq	
^{252}Cf	2.6 y	≤ 10 GBq	
^{210}Po	138 d	≤ 20 GBq	Static eliminators
^{3}H	12.3 y	≤ 10 TBq	Electron capture detectors
^{63}Ni	100 y	≤ 50 GBq	
^{169}Yb	32 d	≤ 1 TBq	Industrial radiography
^{160}Tm	128.6 d	≤ 1 TBq	
^{60}Co	5.3 y	≤ 15 TBq	
^{75}Se	120 d	≤ 2 TBq	
^{192}Ir	74 d	≤ 5 TBq	
^{60}Co	5.3 y	≤ 40 PBq	Sterilisation
^{63}Ni	100 y	<4 MBq	Calibration sources
^{137}Cs	30.17 y	<4 MBq	Anatomical markers
^{57}Co	271.7 d	≤ 400 MBq	Standard sources in instruments
^{226}Ra	1600 y	<10 MBq	
^{147}Pm	2.62 y	<4 MBq	
^{36}Cl	3.01×10^5 y	<4 MBq	
^{129}I	$1.57\ 10^7$ y	<4 MBq	

[1]y = years, d = days, s = seconds, h = hour

Figure 7.1 A typical smoke detector in the International Atomic Energy Agency building.

Smoke detectors containing extremely small amounts of radioactive substances are widely used both at industrial facilities and residential houses (Fig. 7.1). They typically contain ^{241}Am or ^{239}Pu as a source of alpha radiation and two ionisation chambers, one of which is open to ambient air. Alpha particles ionise the air in both ionisation chambers, thus with a small electric voltage applied a small electric current exists in both chambers. In absence of smoke these currents are balanced. When smoke enters the open chamber an imbalance occurs between two currents coming from ionisation chambers so that the alarm is triggered at a certain threshold.

7.5 FOOD PROCESSING AND AGRICULTURE

Ionising radiation is used to stop the sprouting of root crops after harvesting, delay ripening and increase juice yield, and to kill any parasite microorganisms, bacteria, viruses or insects present. Radiation is typically

Table 7.5 Typical doses of gamma radiation in food processing

Application	Dose, Gy
Inhibition of sprouting	3–12
Insect disinfestation	20–80
Parasite disinfestation	10–3000
Shelf-life extension	50–3000
Bacteria sterilisation	1500–1700
Reduction of bacteria in dry food ingredients	3000–20,000
Production of meat and fishery products to shelf-stable at room temperature	25,000–60,000

Food irradiation is currently permitted by over 40 countries and volumes are estimated to exceed 500,000 tonnes.

provided by sealed radioactive sources, X-ray generators or electron accelerators. The average amount of energy imparted for effective food irradiation is shown in Table 7.5 (after Tsoulfanidis, 2018).

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