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Radionuclides handbook

R&D Technical Report P3-101/SP1b

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Environment Agency, Government Buildings,
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Tel: 0117 914 2656 Fax: 0117 914 2673

Authors:
M Kelly, M Thorne*

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This report is a reference document, describing physical, chemical and biological behaviour of radionuclides in the environment. It was produced to complement R&D project P3-101/1a, aimed at assessing possible impact of ionising radiation from authorised discharges on Natura 2000 sites.

Research contractor:
Serco Assurance
424 Harwell, Didcot, Oxfordshire, OX11 0QJ
Tel: +44 (0)1235 433005 Fax: +44 (0)1235 436579

* In conjunction with Mike Thorne and Associates Limited

Environment Agency Project Manager:
Irene Zinger

Executive summary

The completion of Stage 2 of the Environment Agency's Review of Consents process (as required under the Habitats Regulations 1994) has resulted in a number of RSA93 authorisations requiring a detailed (Stage 3) assessment. This requires an understanding of the environmental transfer characteristics, biotic uptake and radiological impact of a wide range of radionuclides. There is a need to draw together the relevant information into a single source document as a wide range of Environment Agency and English Nature staff will be involved in undertaking the Stage 3 assessments. This report addresses that requirement.

The report is split into two parts:

1. An introduction to radioactivity and its properties, along with some of the global characteristics of the radionuclides considered in the Handbook
2. Detailed information for a number of radionuclides that may require consideration in the Stage 3 assessments.

The aim of Part 1 of the report is to provide a basic introduction to radioactivity and its properties in order to set in context the more detailed information provided in Part 2. Part 1 briefly covers the following:

- fundamental facts about atoms and the nature of radioactivity;
- how radiation interacts with matter and the implications for living organisms;
- the radionuclides considered and their inter-relationships;
- the general features described for each radionuclide in Part 2.

Part 2 provides information about 85 radionuclides, including:

- basic properties
- modes of decay
- chemical properties and analogues
- environmental transfer characteristics
- uptake by, and exposure of, biota
- dosimetric issues.

It is not intended to provide an exhaustive set of properties and characteristics in Part 2. Rather, the aim is to provide a basic understanding for the environmental behaviour and radiological significance of the radionuclides and their possible impact on non-human species.

A list of references is given at the end of Part 1, together with some suggestions for additional reading. To help the reader, a substantial glossary is given at the end of the report.

Contents

List of Tables and Figures

Introduction

The completion of Stage 2 of the Environment Agency's Review of Consents process (as required under the Habitats Regulations 1994) has resulted in a number of Radioactive Substances Act 1993 (RSA93) authorisations requiring a full Appropriate Assessment (Stage 3).

The wide range of staff involved in Stage 3 assessments will need to access basic information on the properties of radionuclides to help them understand their impact in the environment. While this information is available from a variety of sources, no single document details the properties and behaviour of the full range of relevant radionuclides in the environment. The aim of this Handbook is to address this and to bring basic information regarding a number of important radionuclides together in a single reference.

The report is divided into two parts.

- Part 1 provides a basic introduction to radioactivity and its properties in order to set in context the more detailed information provided in Part 2.
- The properties of 85 radionuclides that may be relevant to the radiation protection of wildlife are presented in Part 2. The intention is not to provide an exhaustive set of properties and characteristics. Rather, the aim is to provide a basic understanding of the environmental behaviour and radiological significance of a number of radionuclides, and their possible impact on non-human species.

The glossary also includes entries from the glossary given in Environment Agency R&D Publication 128 (Copplestone et al., 2001).

Acknowledgements

The report draws on work carried out by AEA Technology plc on the production of datasheets for a number of radionuclides for the Environment Agency's pollution inventory.

The report was also peer-reviewed by dedicated Agency staff and externally by staff at the University of Liverpool to ensure that the technical content was accurate and reflected people's experiences in this field.

PART 1

Brief introduction to radioactivity and its properties

Fundamental concepts on atoms and the nature of radioactivity are summarised in Section 1. Section 2 goes on to consider how radiation interacts with matter and the possible implications for living organisms, while Section 3 considers some of the general features of the radionuclides covered in Part 2 of the report. Section 4 describes the type of information given in Part 2 and introduces its format. Section 5 lists the references cited in the report and provides some suggestions for additional reading and a short list of useful websites.

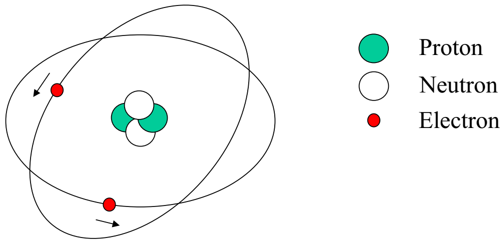
Further information relating to radioactivity and its properties can be obtained from NRPB (1998).

1. Introduction to atoms and radioactivity

All matter is made up from atoms; an atom is the smallest particle that has the physical characteristics of any given element. Atoms are very small - the diameter of the smallest atoms is about 10^{-8} cm. About 114 different species of atom have so far been discovered. Each species of atom defines an element such as oxygen, helium and carbon. Figure 1 shows the first 103 elements in the form of the periodic table.

An atom consists of a nucleus, around which rotates a number of electrons (Figure 2). The radius of the orbits of these electrons is about the same as the atomic size, i.e. 10^{-8} cm. The radius of the nucleus is about 100,000 times smaller. Electrons carry a negative electrical charge, whereas the nucleus carries a positive electrical charge.

The nucleus itself is composed of two types of smaller particle, called protons and neutrons. These particles have similar masses (the neutron is slightly heavier), but they differ in that the proton carries a positive electrical charge (equal in magnitude but opposite to the electron). Protons and neutrons differ in other ways, but these are not relevant to this discussion.



In a simplified model of the atom, electrons rotate around a nucleus consisting of protons and neutrons. The diagram above shows a helium atom.

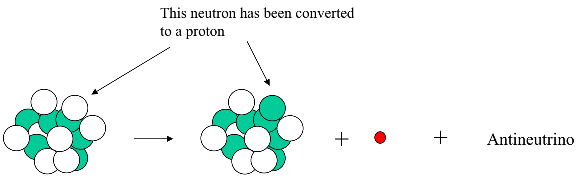
Figure 2: Model of a helium atom

The 114 or so elements are identified in terms of the number of protons in the nucleus. Elements with low atomic number are often referred to as light elements and those with high atomic number are referred to as heavy elements. The lightest element (hydrogen) has only a single proton, whereas the heaviest has 114 protons. Hydrogen has only a single electron rotating around its nucleus, whereas the heaviest has 114 electrons. Each element has:

- an atomic number, Z, i.e. the number of protons in the nucleus;
- a neutron number, N, i.e. the number of neutrons in the nucleus;
- an atomic mass, A, which is the total number of protons plus neutrons.

The vertical columns of the periodic table are referred to as ‘groups’; the elements within a group tend to have similar chemical properties. Thus, for example, sodium (Z = 11) and potassium (Z = 19) both belong to Group 1 and have similar chemical properties. The environmental characteristics of an element for which data are scarce can often be inferred by considering the properties of other better-understood elements in the same group. For further information, see Hill and Holman (2000).

Radioactivity may be defined as a spontaneous nuclear transformation that usually results in the formation of a different nucleus and occurs when the nucleus is moving to a more stable situation by emitting energy or particles. The transformation from one nucleus to another nucleus is called radioactive decay (see the example in Figure 3). Consider a nucleus with Z protons and N (equals A - Z) neutrons. The nucleus can only be stable for certain combinations of Z and N. By 'stable', we mean that the nucleus remains in the same form (with the same Z and N) for an infinite period of time. N is generally greater than Z, but nuclei with more protons that neutrons can occur, e.g. helium-3 has two protons and one neutron.



The decay of carbon-14. This isotope has an excess of neutrons and hence is unstable. It decays by converting a neutron into a proton, with the emission of an electron and an antineutrino.

Figure 3: Radioactive decay of carbon-14

The antineutrino (as illustrated in the decay of carbon-14 in Figure 3) has a negligible mass and carries no charge, and consequently is of little relevance from the perspective of radiation protection. It is not considered further in this report.

As another example, stable cobalt has an atom with 27 protons and 32 neutrons (Z = 27, A = 59), and may be written as cobalt-59, or, more technically, as $^{59}\mathrm{Co}$. However, if the nucleus gains an extra neutron compared with stable cobalt-59, then a new nucleus with Z = 27, A = 60 is formed that is unstable. This is known as cobalt-60 (abbreviated as Co-60), which is said to be radioactive.

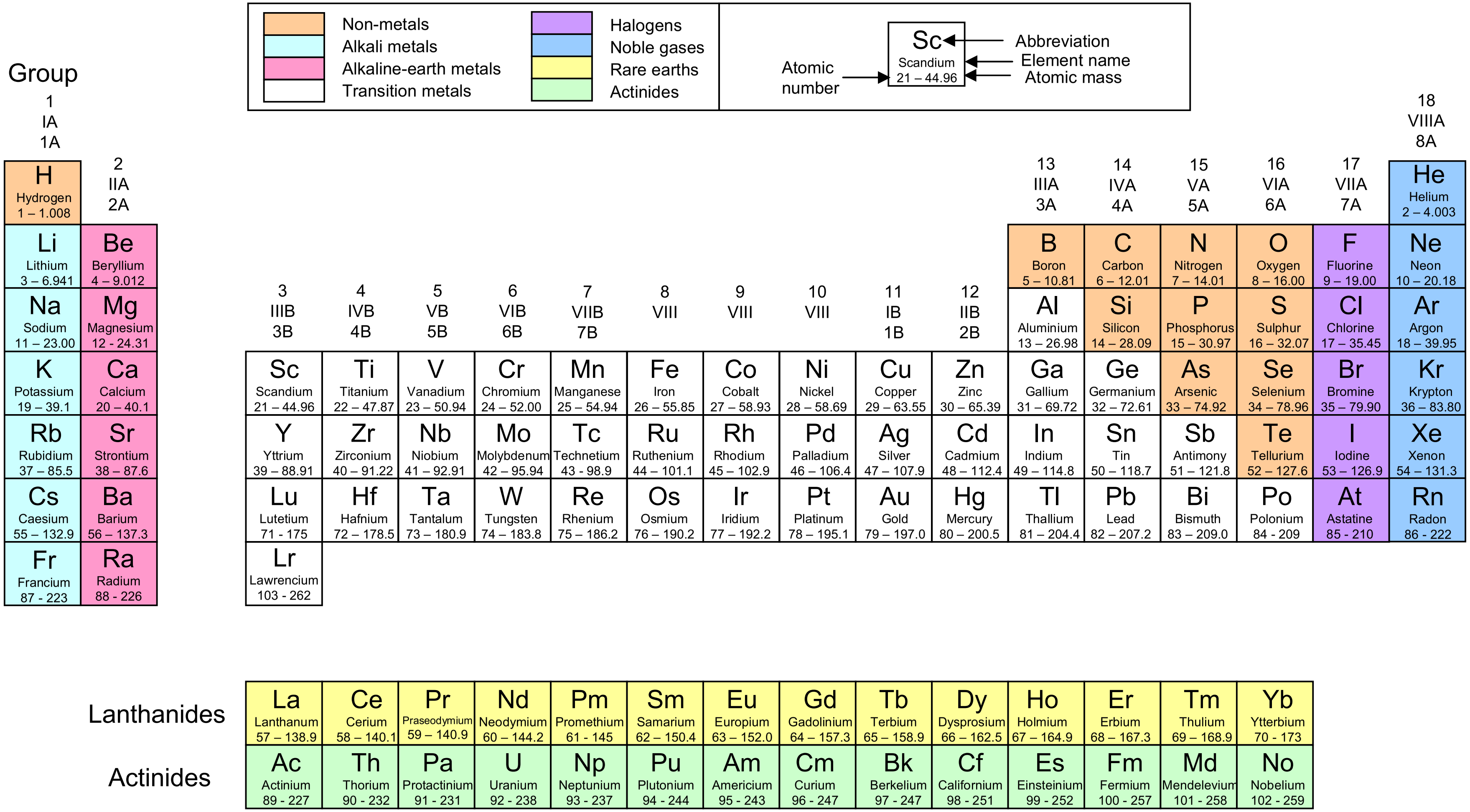
The cobalt-60 nucleus is not stable and can only exist in that form for a limited amount of time. The nucleus eventually changes its form to a configuration that is stable; this involves a change in the numbers of protons and neutrons present. In this case, one of the neutrons becomes a proton and an electron is emitted from the nucleus. As explained later, this electron is called a beta particle. Atoms with nuclei that have the same number of protons but differing number of neutrons are called isotopes. These atoms thus belong to the same element and isotopes of an element have essentially the same chemical properties.

Half-life

It is not possible to predict the exact amount of time that will elapse before any particular unstable nucleus decays. However, if a large number of such nuclei are present, one can define an average decay time. This is related to an important quantity known as the radioactive half-life. This is defined as the time required for half of the nuclei present to decay. In the case of cobalt-60, the radioactive half-life is about 5 years; that is, after about 5 years, we can expect approximately 500 cobalt-60 atoms to be left from 1,000 cobalt-60 atoms.

The existence and decay of atoms with unstable nuclei is the basis for the existence of radiation and radioactivity. In the example of cobalt-60, the radioactive transformation of the nucleus to a more stable form is accompanied by the emission of an electron, as one the neutrons in the nucleus transforms itself into a proton. In the case of cobalt-60, this transformation is also accompanied by the emission of a photon of electromagnetic radiation (called a gamma ray). It is the ultimate fate of these gamma rays and the emitted electron that is of concern when considering the radioactive problems posed by cobalt-60 (cobalt-60 sources are often used in medical applications of radioactivity). This is discussed further in Section 2.

Radionuclide half-lives can vary from very small (for example, polonium-214 has a half-life of 0.00016 seconds) to very large (for example, thorium-232 has a half-life of 1.4 x 10^{10} years). In many cases, short-lived radionuclides are only of limited importance when released into the environment. This is because they will decay before they can be transported through the environment to locations where biota are exposed to them.



🟧 Non-metals
🟦 Alkali metals
🟥 Alkaline-earth metals
⬜ Transition metals
🟪 Halogens
🟦 Noble gases
🟨 Rare earths
🟩 Actinides

Atomic number → Sc Scandium 21 – 44.96
Abbreviation
Element name
Atomic mass

Group 1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII	9 VIII	10 VIII	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
H Hydrogen 1 – 1.008																	He Helium 2 – 4.003
Li Lithium 3 – 6.941	Be Beryllium 4 – 9.012											B Boron 5 – 10.81	C Carbon 6 – 12.01	N Nitrogen 7 – 14.01	O Oxygen 8 – 16.00	F Fluorine 9 – 19.00	Ne Neon 10 – 20.18
Na Sodium 11 – 23.00	Mg Magnesium 12 - 24.31											Al Aluminium 13 – 26.98	Si Silicon 14 – 28.09	P Phosphorus 15 – 30.97	S Sulphur 16 – 32.07	Cl Chlorine 17 – 35.45	Ar Argon 18 – 39.95
K Potassium 19 – 39.1	Ca Calcium 20 – 40.1	Sc Scandium 21 – 44.96	Ti Titanium 22 – 47.87	V Vanadium 23 – 50.94	Cr Chromium 24 – 52.00	Mn Manganese 25 – 54.94	Fe Iron 26 – 55.85	Co Cobalt 27 – 58.93	Ni Nickel 28 – 58.69	Cu Copper 29 – 63.55	Zn Zinc 30 – 65.39	Ga Gallium 31 – 69.72	Ge Germanium 32 – 72.61	As Arsenic 33 – 74.92	Se Selenium 34 – 78.96	Br Bromine 35 – 79.90	Kr Krypton 36 – 83.80
Rb Rubidium 37 – 85.5	Sr Strontium 38 – 87.6	Y Yttrium 39 – 88.91	Zr Zirconium 40 – 91.22	Nb Niobium 41 – 92.91	Mo Molybdenum 42 – 95.94	Tc Technetium 43 - 98.9	Ru Ruthenium 44 – 101.1	Rh Rhodium 45 – 102.9	Pd Palladium 46 – 106.4	Ag Silver 47 – 107.9	Cd Cadmium 48 – 112.4	In Indium 49 – 114.8	Sn Tin 50 – 118.7	Sb Antimony 51 – 121.8	Te Tellurium 52 – 127.6	I Iodine 53 – 126.9	Xe Xenon 54 – 131.3
Cs Caesium 55 – 132.9	Ba Barium 56 – 137.3	Lu Lutetium 71 - 175	Hf Hafnium 72 – 178.5	Ta Tantalum 73 – 180.9	W Tungsten 74 – 183.8	Re Rhenium 75 – 186.2	Os Osmium 76 – 190.2	Ir Iridium 77 – 192.2	Pt Platinum 78 – 195.1	Au Gold 79 – 197.0	Hg Mercury 80 – 200.5	Tl Thallium 81 – 204.4	Pb Lead 82 – 207.2	Bi Bismuth 83 – 209.0	Po Polonium 84 - 209	At Astatine 85 - 210	Rn Radon 86 - 222
Fr Francium 87 - 223	Ra Radium 88 - 226	Lr Lawrencium 103 - 262															

Lanthanides	La Lanthanum 57 – 138.9	Ce Cerium 58 – 140.1	Pr Praseodymium 59 – 140.9	Nd Neodymium 60 – 144.2	Pm Promethium 61 - 145	Sm Samarium 62 – 150.4	Eu Europium 63 – 152.0	Gd Gadolinium 64 – 157.3	Tb Terbium 65 – 158.9	Dy Dysprosium 66 – 162.5	Ho Holmium 67 – 164.9	Er Erbium 68 – 167.3	Tm Thulium 69 – 168.9	Yb Ytterbium 70 - 173
Actinides	Ac Actinium 89 - 227	Th Thorium 90 - 232	Pa Protactinium 91 - 231	U Uranium 92 - 238	Np Neptunium 93 - 237	Pu Plutonium 94 - 244	Am Americium 95 - 243	Cm Curium 96 - 247	Bk Berkelium 97 - 247	Cf Californium 98 - 251	Es Einsteinium 99 - 252	Fm Fermium 100 - 257	Md Mendelevium 101 - 258	No Nobelium 102 - 259

Figure 1: The periodic table (the first 103 elements)

Modes of decay

The most common modes of radioactive decay are:

- alpha decay
- beta decay
- gamma emission as isomeric transformation (IT)
- X-ray emission, e.g. electron capture (EC)
- neutron.

Each of these modes of decay is explained below.

Alpha decay (α)

Alpha decay is a type of radioactive decay in which the nucleus emits an alpha particle - a particle that consists of two protons and two neutrons bound together. An alpha particle is in fact a helium nucleus. The alpha particle is emitted with an energy that is characteristic of the nucleus undergoing the decay.

Plutonium-239 is an example of a radionuclide that undergoes alpha decay. The alpha decay of plutonium-239 can be written as follows:

$${}^{239}_{94}\text{Plutonimum} \rightarrow {}^{235}_{92}\text{Uranium} + {}^{4}_{2}\text{Helium}$$

With a few exceptions, alpha decay is only observed in nuclei with more than 82 protons.

Alpha decay is of greatest radiological importance for internally incorporated radionuclides.

Beta decay (β)

- Beta decay is the emission of electrons. They are most commonly negatively charged (written as β^-), but are sometime positively charged, when they are called positrons (written as β^+). In this type of decay either a neutron is converted to a proton and the nucleus emits an electron, for example:

$${}^{131}_{53}\text{Iodine} \rightarrow {}^{131}_{54}\text{Xenon} + \beta^- \quad \text{or}$$

- a proton is converted into a neutron and the nucleus emits a positron (a positively charged electron), for example:

$${}^{22}_{11}\text{Sodium} \rightarrow {}^{22}_{10}\text{Neon} + \beta^+$$

The positron produced in the decay of sodium-22 interacts with an electron and both 'destroy', giving rise to two gamma rays (each of energy 0.511 MeV).

In contrast to alpha decay, the energy of the emitted beta particle can assume any value from zero up to a maximum value. Calculations of beta doses for radiation protection generally use the average energy of emission, which is about a third of the maximum value. Beta decay is often accompanied by the emission of one or more gamma rays.

Beta decay is of radiological importance for internally incorporated radionuclides and external irradiation.

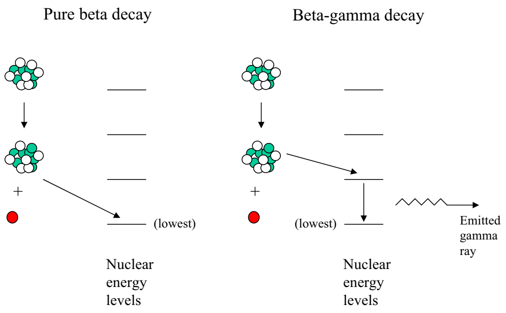
Gamma decay (γ)

Gamma rays are pulses of electromagnetic radiation (called photons) that are emitted when the nucleus undergoes an internal rearrangement of its constituent protons and neutrons. The energy of the gamma ray is equal to the energy difference between the initial and final (lower) energy states of the nucleus, and the emission is required to conserve energy. Radiowaves, microwaves and visible light are more familiar examples of electromagnetic radiation.

Usually, a gamma ray is emitted following beta decay (and occasionally alpha decay). Once the decay has occurred, the resultant nucleus is left in one of its higher energy states. It moves back down to its lowest energy state by emitting one or more gamma rays.

As illustrated in Figure 4, two types of beta decay are often considered in radiation protection, as not all beta emitters emit a gamma ray:

- pure beta emitters emit beta particle only, e.g. hydrogen-3;
- beta-gamma emitters emit beta particles and gamma rays, e.g. cobalt-60.



In pure beta decay, the resultant nucleus is in its ground state.
In beta-gamma decay, the resultant nucleus is in an excited
state, and returns to the ground state by emitting a gamma ray.

Figure 4: Types of beta decay

In many cases, the gamma rays are of greater radiological significance. Thus, cobalt-60 decays by beta decay, but the gamma rays are the most important when assessing the radiological consequences of cobalt-60.

Another important class of radionuclides is those that beta decay to a metastable radionuclide (see below under isomeric transformation), which in turn emits a gamma ray when it decays. An example is caesium-137, which beta decays to barium-137m (an excited state of barium-137), which in turn emits a gamma ray as it decays to stable barium-137. In 89 % of subsequent decays of barium-137m, excess energy is lost by emitting a gamma ray and, in the remaining 11 % of cases, by internal conversion (see below under X-ray emission). Once again, it is the gamma ray emitted by barium-137m that is of greater significance than the beta particle emitted by caesium-137.

Gamma rays can be emitted without any previous alpha or beta decays by certain metastable species such as Tc-99m and In-113m. These emit gamma rays when they decay from their excited states to the ground state via an isomeric transformation of the nucleus.

Gamma decay is of greatest radiological importance in the context of external irradiation. For larger species, however, internally incorporated gamma emitters are also important.

Isomeric transformation (IT)

The release of gamma radiation from alpha or beta decay is sometimes delayed and the daughter nucleus survives in a higher energy state (the metastable state) for some time before it returns to a lower energy state by emitting gamma rays. This form of decay is called an isomeric transformation and the metastable state is denoted by the letter ‘m’ after the atomic mass, for example, technetium-99m. Technetium-99m decays to technetium-99 via an isomeric transformation, emitting a gamma ray as it does so.

X-ray emission

X-ray emission arises during a type of radioactive decay known as internal conversion. Instead of shedding its excess energy by emitting a gamma ray, an excited nucleus can dispose of its excess energy by interacting with one of the inner electrons orbiting the nucleus. This electron in turn absorbs the excess energy and is ejected from the atom. When internal conversion occurs, other orbiting electrons can ‘fall’ into the orbit vacated by the ejected electron. When this happens, the electron loses energy, and an X-ray is emitted.

Orbital electron capture (EC) is another process that produces X-rays. Here, the nucleus captures one of the electrons orbiting the nucleus. As above, X-rays are emitted as the orbiting electrons rearrange themselves to fill the orbit vacated. The electron interacts with one of the protons to produce a neutron and a neutrino is ejected from the nucleus. The neutrino, however, has no radiological significance. Sodium-22 can decay by orbital electron capture, as well as by positron emission.

An outer electron falls into the vacancy left by the captured electron and an X-ray is emitted.

Neutrons

Neutrons are usually produced in a laboratory or nuclear reactor when a nuclear transformation is induced, for example, by taking an atom and firing another nuclear particle at it, or when radioactive fission occurs. Fission is the breaking up of a large unstable nucleus into two roughly equal nuclei, each around half the size of the original; this process liberates considerable amounts of energy. The effects of neutrons will not be considered further in the context of environmental radioactivity.

The modes of radioactive decay discussed above lead to the production of new nuclides from the original. In some cases, the new nuclide will be stable. However, successive decays can lead to new radioactive species. In such cases, radioactive decay chains are formed. Figure 5 shows the decay chain for uranium-238.

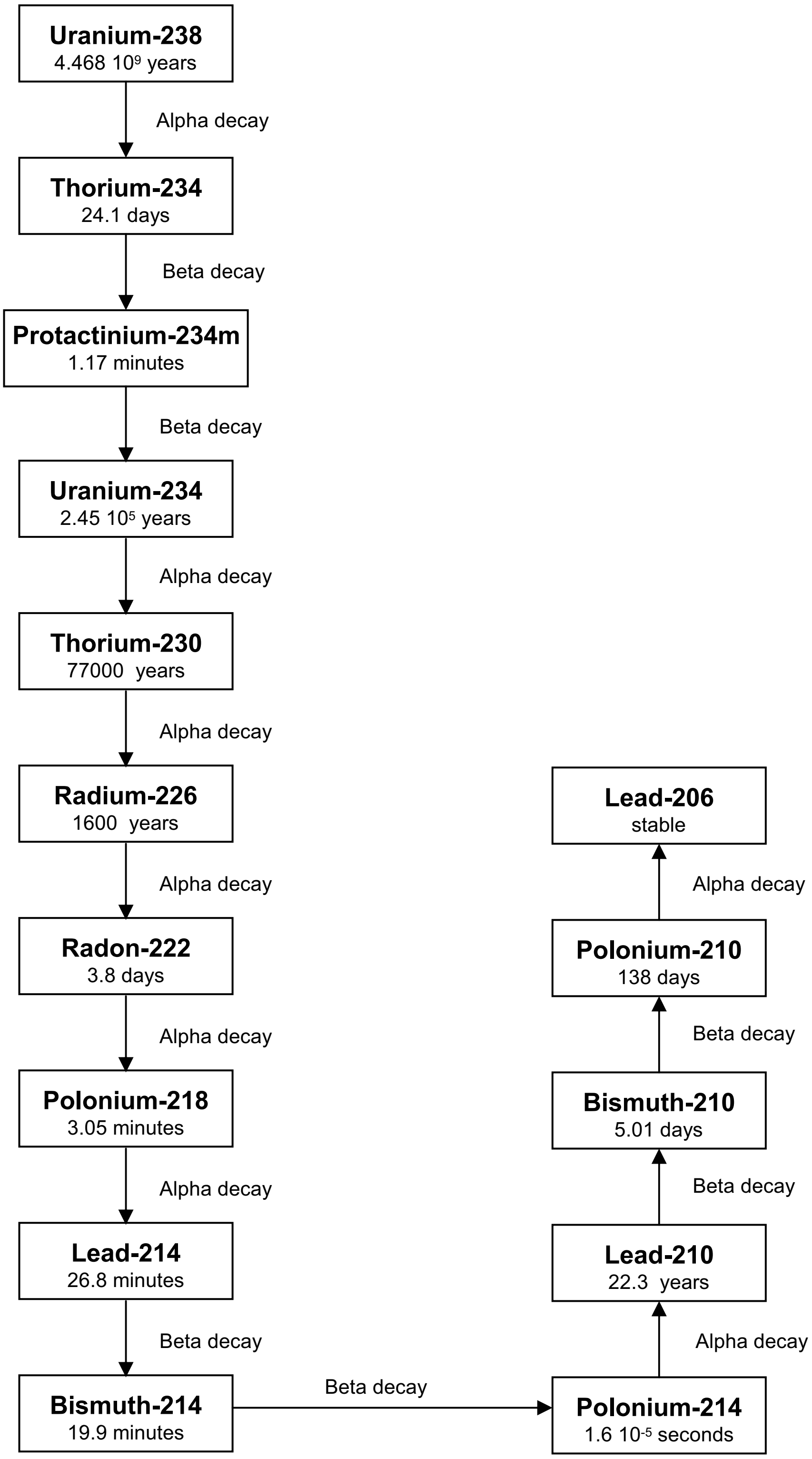


Figure 5: Example of a radioactive decay chain *(decay data from ICRP Publication 38)*

2. Effects of radiation on matter and wildlife

The previous section described how radioactive decay can lead to the following by-products:

- alpha particles (helium nuclei)
- beta particles (electrons or positrons)
- gamma rays (high energy electromagnetic radiation)
- X-rays.

To appreciate why these types of radiation are potentially damaging to living entities, it is necessary to understand how they interact with matter and, in particular, living tissue and cells. It should be borne in mind that, just like all other matter, living tissue consists of a collection of atoms and molecules bound together to form the tissue mass. As before, further information relating to the effects of radiation on matter can be obtained from NRPB (1998).

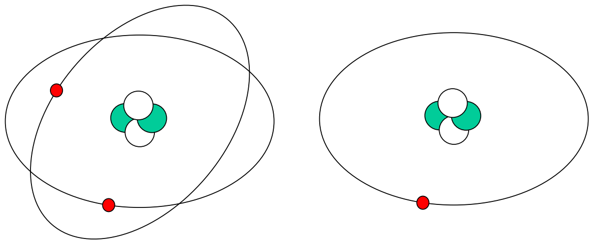
Alpha and beta particles

Alpha and beta particles (and other charged particles) are often referred to as directly ionising radiation. This is because, when an alpha or beta particle enters living tissue, it interacts directly with the outer electrons of the constituent atoms and, if it supplies enough energy, it can knock the outer electrons away from the atoms. The end products of such an event are a free electron and a positively charged ion. This process is called ionisation (see Figure 6) and is the basic physical mechanism that gives rise to radiological detriment and harm.

Because alpha and beta particles have substantially different masses and different charges, the rates at which the two types of particle cause ionisation are very different:

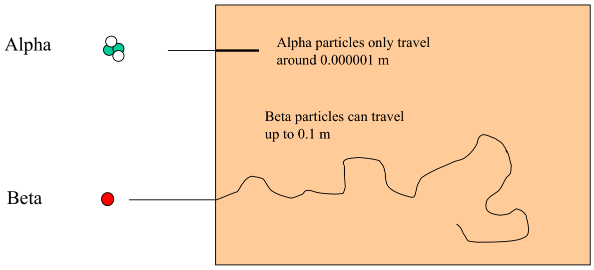
- beta particle produces >100 ionisation events per cm of travel;
- alpha particle produces >10,000 ionisation events per cm of travel.

Alpha particles therefore cause considerably more ionisations (and hence radiological damage). However, as shown in Figure 7, this is partly offset by the fact that alpha particles have a very much smaller range of travel in body tissue than beta particles of the same energy (of the order of micrometres compared with centimetres for beta particles). As the energy of either particle increases, so the range increases.



Ionisation of the helium atom. The helium ion on the right has lost an electron, compared with the neutral helium atom on the left.

Figure 6: Example of the ionisation of an atom



Alpha particles and beta particles show different behaviour when interacting with matter. Alphas, on account of their mass, tend to follow straight paths, whereas the much lighter beta particles tend to follow more random paths.

Figure 7: Relative range of travel of alpha and beta particles

A consequence of this is that alpha-emitting radioisotopes rarely pose a radiological hazard outside the body, as the alpha particles are not able to penetrate through skin. When alpha particles are taken into the body, for example by inhalation into the lung, the radiological hazard is high due to the very high rate of ionisation as they slow down in lung tissue.

Gamma rays

In contrast to alpha and beta particles, gamma rays induce ionisation in the atoms of living tissue by indirect means (the result of indirect ionising radiation). There are three principal mechanisms by which gamma rays interact with living tissue:

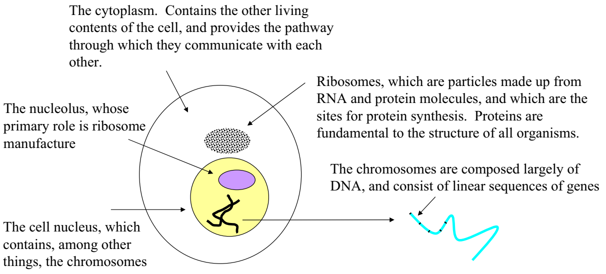
- Compton scattering
- photoelectric effect
- pair production.

In the Compton effect, the gamma rays are scattered from the outer electrons of the atoms, transferring energy to the electrons and in the process reducing the energy of the gamma ray. If enough energy is supplied during scattering, the outer electron will be removed from the atom, leaving an ion and giving rise to a free electron.

The photoelectric effect and pair production mechanisms are important for low and high gamma energies, respectively. For the gamma rays emitted by the majority of radionuclides, this can pose an environmental hazard. Compton scattering is the most important interaction mechanism.

Microscopic effects of radiation

To understand the nature of the damage caused by radiation, it is necessary to look at the microscopic structure of living organisms. Any living animal or plant is composed of a large number of individual cells (see Figure 8). These cells can be split broadly into two categories, namely somaticm cells and germ cells. Germ cells are responsible for the reproduction of offspring and constitute the sperm in males and the ova in females. All other cells fall under the classification of somatic cells.



The cell. The above is a very simplified picture of a typical cell in animals and humans. The characteristics (e.g. hair colour, blood group) of an individual is determined by thecomposition of the genes, from which the chromosomes are composed. DNA forms a “chemical” template for protein synthesis, which in turn is mediated by RNA.

Figure 8: The cell

The genetic information that characterises any individual is contained within the chromosomes. In dogs, for example, the somatic cells contain 78 chromosomes (39 chromosomes occurring in pairs) and germ cells contain 39 chromosomes (39 chromosomes occurring once), so that when a sperm and an ovum come together they produce a composite with the full 78 chromosomes. All cells in the body contain exactly the same genetic information; when cells divide, the chromosomes are reproduced exactly so that the new cells resulting from cellular division contain exactly the same genetic information as in the original cell.

Suppose that a collection of cells in a living organism is subject to the types of radiation described above. The main effect of this radiation is to cause ionisation of the atoms in the absorbing medium. Thus, when cells are irradiated, it is likely that ionisation of one or more of the atoms on some of the DNA molecules will occur. This can lead to a number of consequences for the affected molecule. These effects include:

- breakage of the chains of molecules comprising the DNA;
- breakage of the links between chains.

In many cases, the cell is able to repair the damage, but not always. For example, single-strand breaks within DNA can often be repaired without error, whereas double-strand breaks cannot. When the damage cannot be repaired, the affected cell is left with altered or damaged genetic information compared with the unaffected cells. All descendants of that cell will also contain altered or damaged information because cellular division results in exact replication of the genetic information in the original cell.

The multiplication of damaged cells in this way is the basis for the induction of cancer in mammals. However, in the context of wildlife populations, a number of alternative endpoints have been identified that can be studied after exposure to radiation. These include:

- morbidity, e.g. illness and lifetime shortening;
- mortality;
- changes in reproductive capacity (including fertility and fecundity);
- mutation.

UNSCEAR (1996) provides a useful review of studies relating to the effects of ionising radiation on non-human species. UNSCEAR (1996) concluded that, overall, the general capacity of plant communities to withstand general stresses and changes within the environment also enables them to withstand low to moderate radiation stress. There may be alterations to community structure and morphological changes to individual plants (depending on the level of radiation exposure), but the compensations are generally such as to maintain a normal energy balance.

Changes in animal communities in terrestrial environments seem mainly to arise indirectly as a consequence of changes to the plant community. When plant species die in highly irradiated areas, the food supplies of herbivorous animals and their predators are reduced. These animals may disappear and be replaced by species that depend on dead and decaying material. Some of these species may further damage remaining vegetation, which might otherwise have survived.

Because of the compensation and adjustment possible in animal species, UNSCEAR (1996) considered it unlikely that radiation exposures causing only minor effects in the most exposed individual would have significant effects on the population. Similar views are expressed in respect to aquatic communities.

Studies and interpretation of the effects of radiation on non-human species are ongoing. One example is the EC 5th Framework Programme project, FASSET (Framework for ASSessment of Environmental impacT). A recent output from this project is a report by Woodhead and Zinger (2003) on radiation effects to plants and animals.

3. Radionuclides considered

For this study, 85 radionuclides of possible environmental significance to wildlife have been considered. Many of these radionuclides originate from medical or industrial applications, or are by-products of nuclear power generation. Total alpha emitters, total beta emitters and depleted uranium are also considered.

The selection of radionuclides originate from:

- the Environment Agency's knowledge of radionuclides present in regulatory authorisations;
- those identified by FASSET (Strand et al., 2001);
- those used in assessment spreadsheets contained in Agency guidance on implementing the Habitats Regulations 1994 (Allott and Dunn, 2001).

Table 1 lists the chosen radionuclides detailed in Part 2. For a few elements, some radionuclides are produced under two forms, for example, Tc-99 and Tc-99m. The 'm' stands for 'metastable' (see Section 2). The Tc-99m nucleus has the same structure as the Tc-99 nucleus, but exists in a higher energy state and can remain there for a reasonably long period of time. It decays to Tc-99 by emitting a gamma ray.

More detailed information for these radionuclides is provided in Part 2 in the form of two-page summaries of their key properties and characteristics, catalogued by radionuclide symbol, for example, Au-98 and Cs-137 (and not element name). The purpose of the Handbook is not to provide an exhaustive set of properties and characteristics for all radionuclides. The aim is rather to provide an insight into the environmental behaviour and radiological significance of the radionuclides for non-human species.

The use of numerical parameters has been avoided where possible, although in some cases order-of-magnitude estimates of transfer parameters have been given to provide an indication of radionuclides and species that are assimilated with particular efficiency into biological systems.

At the beginning of Part 2, radionuclides are listed by their symbols (e.g. Cs-137) and an index is given which points to their location in the Handbook.

Table 1 Selection of radionuclides for the Handbook

Element	Radionuclide	Symbol	Origin of selection
Americium	Americium-241	Am-241	FASSET, Pub128
Antimony	Antimony-125	Sb-125	Agency
Argon	Argon-41	Ar-41	Pub128
Bromine	Bromine-82	Br-82	Agency
Caesium	Caesium-134	Cs-134	FASSET
	Caesium-135	Cs-135	FASSET
	Caesium-137	Cs-137	FASSET, Pub128
Calcium	Calcium-45	Ca-45	Agency
	Calcium-47	Ca-47	Agency
Carbon	Carbon-11	C-11	Agency
	Carbon-14	C-14	FASSET, Pub128
Cerium	Cerium-144	Ce-144	Agency
Chlorine	Chlorine-36	Cl-36	FASSET, Agency
Chromium	Chromium-51	Cr-51	Agency
Cobalt	Cobalt-57	Co-57	Agency
	Cobalt-58	Co-58	Agency
	Cobalt-60	Co-60	Pub128
Curium	Curium-242	Cm-242	FASSET
	Curium-243	Cm-243	FASSET
	Curium-244	Cm-244	FASSET
Erbium	Erbium-169	Er-169	Agency
Fluorine	Fluorine-18	F-18	Agency
Gallium	Gallium-67	Ga-67	Agency
Gold	Gold-198	Au-198	Agency
Indium	Indium-111	In-111	Agency
	Indium-113m	In-113m	Agency
Iodine	Iodine-123	I-123	Agency
	Iodine-125	I-125	Pub128
	Iodine-129	I-129	FASSET, Pub128
	Iodine-131	I-131	FASSET, Pub128
Iron	Iron-59	Fe-59	Agency
Krypton	Krypton-79	Kr-79	Agency
	Krypton-81	Kr-81	Agency
	Krypton-85	Kr-85	Pub128
Lanthanum	Lanthanum-140	La-140	Agency
Lead	Lead-210	Pb-210	FASSET
Manganese	Manganese-54	Mn-54	Agency
	Manganese-56	Mn-56	Agency
Molybdenum	Molybdenum-99	Mo-99	Agency
Neptunium	Neptunium-237	Np-237	FASSET
Nickel	Nickel-59	Ni-59	FASSET
	Nickel-63	Ni-63	FASSET
Niobium	Niobium-94	Nb-94	FASSET
	Niobium-95	Nb-95	Agency

Agency = Environment Agency
Pub128 = R&D Publication 128
N/A = not applicable

FASSET = Framework for ASSessment of Environmental ImpacT (EC 5th Framework project)

Table 1 | continued

Element	Radionuclide	Symbol	Origin of selection
Oxygen	Oxygen-15	O-15	Agency
Phosphorus	Phosphorus-32	P-32	Pub128
	Phosphorus-33	P-33	Agency
Plutonium	Plutonium-238	Pu-238	FASSET
	Plutonium-239	Pu-239	FASSET, Pub128
	Plutonium-240	Pu-240	FASSET
	Plutonium-241	Pu-241	FASSET
Polonium	Polonium-210	Po-210	FASSET, Pub128
Potassium	Potassium-40	K-40	FASSET
Promethium	Promethium-147	Pm-147	Agency
Protactinium	Protactinium-234m	Pa-234m	Agency
Radium	Radium-226	Ra-226	FASSET, Pub128
Radon	Radon-222	Rn-222	Agency
Rhenium	Rhenium-186	Re-186	Agency
Rubidium	Rubidium-81	Rb-81	Agency
	Rubidium-86	Rb-86	Agency
Ruthenium	Ruthenium-106	Ru-106	FASSET, Pub128
Samarium	Samarium-153	Sm-153	Agency
Selenium	Selenium-75	Se-75	Agency
Sodium	Sodium-22	Na-22	Agency
	Sodium-24	Na-24	Agency
Strontium	Strontium-89	Sr-89	FASSET, Pub128
	Strontium-90	Sr-90	FASSET, Pub128
Sulphur	Sulphur-35	S-35	Pub128
Technetium	Technetium-99	Tc-99	FASSET, Pub128
	Technetium-99m	Tc-99m	Agency
Thallium	Thallium-201	Tl-201	Agency
Thorium	Thorium-227	Th-227	FASSET
	Thorium-228	Th-228	FASSET
	Thorium-230	Th-230	FASSET
	Thorium-231	Th-231	FASSET
	Thorium-232	Th-232	FASSET
	Thorium-234	Th-234	Pub128
Total alphas	N/A	N/A	Agency
Total Betas	N/A	N/A	Agency
Tritium	Tritium	H-3	FASSET, Pub128
Uranium	Uranium-234	U-234	FASSET
	Uranium-235	U-235	FASSET
	Uranium-238	U-238	FASSET, Pub128
	Depleted uranium	N/A	Agency
Vanadium	Vanadium-48	V-48	Agency
Xenon	Xenon-133	Xe-133	Agency
Yttrium	Yttrium-90	Y-90	Agency
Zirconium	Zirconium-95	Zr-95	Agency

Agency = Environment Agency
Pub128 = R&D Publication 128
N/A = not applicable

FASSET = Framework for ASSessment of Environmental ImpacT (EC 5th Framework project)

4. Radionuclide data detailed in Part 2

Basic information is supplied on the physical, chemical, environmental and dosimetric behaviour of some 85 radionuclide.

The Handbook is set out in alphabetical order of the symbol for each radionuclide (e.g. Ga-67 and In-111) rather than the name of the element. Table 1 can be used to identify the correct radionuclides, based on their element.

For ease of reference, the page layout for each radionuclide is identical. Each part of the template is explained below.

Name	
Symbol	
Origin	

Name
The name of the element of which the radionuclide is an isotope and its mass number.

Symbol
The usual symbol for the radionuclide

Origin
A classification to indicate how the radionuclide is produced or arises. Where more than one of these applies to a radionuclide, the principal mode of origin is listed. There are six possible choices (see Figure 9 and Part 2).

- Activation. The process in which non-radioactive elements are converted to radioactive elements as a result of exposure to radiation in a nuclear reactor or weapon explosion. An example is the formation of techetium-99m for medical purposes from the irradiation of molydenum-99.
- Breeding. The production of one radionuclide from another due to the action of incident atomic particles. An example is the production of plutonium-239 from uranium-238.
- Cosmogenic. These are radionuclides produced in the upper atmosphere due to the action of cosmic rays.
- Fission. A nuclear reaction in which an atom of large atomic mass splits into two atoms of smaller mass, with the production of one or more neutrons and the release of energy.
- Primordial. These are radionuclides left over from the creation of the universe. They necessarily have very long half-lives, for example, uranium-238 and thorium-232.
- Radiogenic. A term applied to radionuclides that arise from the decay of other radionuclides.

Radioactive half-life	
Principal decay mode	
Grouping	

Radioactive half-life
The half-life of the radionuclide

Principle decay mode
The principal mode of radioactive decay for the radionuclide as described in Section 2. Figure 10 shows the allocation of the investigated radionuclides into the four groups referred to in Part 2. The four groups are as follows.

- Alpha. Nuclear particles consisting of fast-moving helium nuclei (atomic mass of 4 and atomic number 2).
- Beta. A negatively charged (electron) or positively charged (positron) particle emitted from the nucleus of an atom during radioactive decay.
- X-ray as orbital electron capture (EC). A form of radioactive decay in which the nucleus captures an orbiting electron, converting a proton to a

neutron. The energy is released as gamma or X-rays.

- Gamma as isomeric transformation (IT). Very penetrating electromagnetic radiation frequently emitted from the nucleus of an atom during radioactive decay. IT is a form of radioactive decay in which a metastable nucleus decays with the release of energy as gamma rays.

For some radionuclides, the principal decay mode is not the one of greatest significance from a radiation protection perspective. For example, in the decay of cobalt-60, the gamma rays emitted are of greater importance than the beta particle. Where this is the case, the most radiologically significant emissions are given in square brackets.

Grouping

An indication of whether the radionuclide arises naturally in the environment or by artificial means (for example, in a nuclear reactor). The options for this box are 'natural' or 'artificial'.

Parent	
Daughter	
Detection	

Parent

The radionuclide(s) whose decay would give rise to the radionuclide. This entry is set to 'N/A' if the parent is not produced naturally or artificially in significant quantities.

Daughter

The nuclide that arises from decay of the radionuclide; it may be radioactive or stable. Where the daughter is itself radioactive, it is followed by a capital R in square brackets, i.e. [R].

Detection

An indication of whether the radionuclide can be detected 'in the field' or whether laboratory analysis is required. The options are 'in situ' and 'laboratory'. As a general rule, strong gamma emitters can be detected easily in situ, or even by aerial monitoring with a fixed-wing aircraft. Radionuclides that only have weak or zero gamma emissions usually have to be identified from sample analysis in a laboratory (alpha and beta particles have limited ranges in air).

Production Uses		
Modes of release	Land	
	Air	
	Water	

Production, uses and modes of release

Figure 11 groups the radionuclides according to their main industrial, medical and research applications.

Decay modes (graphs)

Information about the modes of decay for each radionuclide is provided in the form of two graphs. The first provides an indication of the energies of the various emissions during decay, along with the fraction of decays that give rise to each emission. The second provides an indication of the nuclear transformations that arise during each decay. For example, the two graphs for strontium-90 are shown in Figure 12.

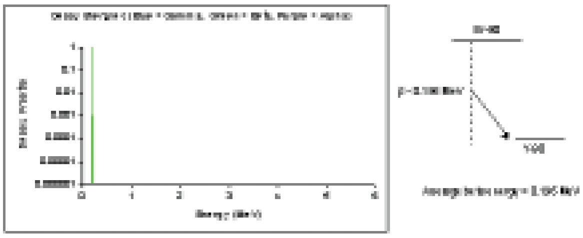


Figure 12: Decay mode graphs for strontium-90

The left-hand graph shows the decay energies and decay fractions. The right-hand graph is a simplified decay scheme, which indicates the nuclear transformation that takes place during the beta decay of strontium-90. Decay data were obtained from ICRP Publication 38.

Chemical properties/characteristics

Speciation	Analogue species
The chemical properties of the element of which the radionuclide is an isotope.	Other elements or radionuclides that show similar chemical, environmental or radiological behaviour to the radionuclide. Table 2 gives an overview of the proposed substitutes.

The chemical properties of most elements can most easily be described using the concept of oxidation number. The oxidation number is the number of electrons that must be added to a positive ion or removed from a negative ion to produce a neutral atom. Thus, for example, for vanadium in an oxidation state of +5, five electrons must be added to produce neutral vanadium.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
A description of the key features of the behaviour of the radionuclide in the terrestrial, aquatic and atmospheric environments Most radionuclides listed in the Handbook are particle reactive and will become bound in sediments or soil. Table 3 summarises the behaviour of radionuclides (i.e. particle reactive versus conservative).		

Exposure routes and pathways

Environmental sink	Intake and uptake routes
A description of the ultimate fate of the radionuclide in the environment	A description of the most important radionuclide uptake routes for biota

Effects on organisms

Dose effects/dosimetry	Species-specific considerations
A description of the key radiological hazards posed by the radionuclide when taken up by biota.	Specific issues relating to particular biota - for example species that might acquire particularly high radiation doses

Table 2 Radionuclide analogues, listed by radionuclide symbol

Symbol	Analogue(s)
Am-241	2nd = Cm None
Ar-41	Ne, Ar, Kr, Xe
Au-198	None
Br-82	Cl
C-11	C-12 C-13 C
C-14	C-12 C-13 C
Ca-45	Ca, Sr, Sr-90
Ca-47	Ca, Sr, Sr-90
Ce-144	Am, 2nd = Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu
Cl-36	Cl Cl
Cm-242	Am None
Cm-243	Am None
Cm-244	Am None
Co-57	Co for plants
Co-58	Co for plants
Co-60	Co for plants Cs-137 (a, f) Sr-90 (m)
Cr-51	Cr
Cs-134	K K
Cs-135	K K
Cs-137	K K
Depleted Uranium	U-238
Er-169	Am, 2nd = Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu
F-18	None
Fe-59	Fe
Ga-67	Ga
H-3	H H Ca-14
I-123	I
I-125	I I-129
I-129	I
I-131	I Cs-137
In-111	None
In-113m	None
K-40	Cs (2nd) K
Kr-79	Ne, Ar, Kr, Xe
Kr-81	Ne, Ar, Kr, Xe
Kr-85	Ne, Ar, Kr, Xe
La-140	Am, 2nd = Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu
Mn-54	Mn
Mn-56	Mn
Mo-99	Mo
Na-22	Na for animals
Na-24	Na for animals
Nb-94	Zr None
Nb-95	Zr
Ni-59	Ni Ni
Ni-63	Ni Ni
Np-237	Np None
O-15	O
P-32	PO4$^-$ Cs-137
P-33	PO4$^-$ Cs-137
Pa-234m	None
Pb-210	Pb, Ca None
Pm-147	Ce, Sm, Eu, Pm
Po-210	Pb-210 None
Pu-238	Pu , 2nd = Np, Am, Cm None
Pu-239	Pu , 2nd = Np, Am, Cm None
Pu-240	Pu , 2nd = Np, Am, Cm None
Pu-241	Pu , 2nd = Np, Am, Cm None
Ra-226	2nd = Ca, Sr, Ba Ca
Rb-81	K, Cs
Rb-86	K, Cs
Re-186	None
Rn-222	None
Ru-106	None Cs-137
S-35	S Cs-137 (f, m)
Sb-125	None
Se-75	Se, S
Sm-153	Ce, Eu, Sm
Sr-89	Ca Ca
Sr-90	Ca Ca
Tc-99	Tc N (NO3$^-$)
Tc-99m	Tc Cs-137
Th-227	Th
Th-228	Th None
Th-230	Th None
Th-231	Th None
Th-232	Th None
Th-234	Th
Tl-201	K
Total alpha	None Ra-226 (a), U-238 (f, m)
Total beta	None Cs-137 (a), Sr-90 (f, m)
U-234	U None U-238
U-235	U None U-238
U-238	U None
V-48	V
Xe-133	Ne, Ar, Kr, Xe
Y-90	Ce, Sr-90
Zr-95	Nb

🟧	FASSET (Strand et al., 2001)
🟦	Agency ‘Stage 2’ (Allott and Dunn, 2001):

a = air
f = freshwater
m = marine waters

Table 3 Behaviour of radionuclides, listed by radionuclide symbol

Symbol	C or P	Symbol	C or P
Am-241	P	Ni-59	P
Ar-41	C	Ni-63	P
Au-198	P	Np-237	P
Br-82	C	O-15	-
C-11	C	P-32	C+P
C-14	C	P-33	C+P
Ca-45	P	Pa-234m	- as Th (P)
Ca-47	P	Pb-210	P
Ce-144	P	Pm-147	P
Cl-36	C	Po-210	P
Cm-242	P	Pu-238	P
Cm-243	P	Pu-239	P
Cm-244	P	Pu-240	P
Co-57	P	Pu-241	P
Co-58	P	Ra-226	-
Co-60	P	Rb-81	C+P
Cr-51	C+P	Rb-86	C+P
Cs-134	P	Re-186	-
Cs-135	P	Rn-222	-
Cs-137	P+C	Ru-106	P
Er-169	P	S-35	C+P
F-18	-	Sb-125	C
Fe-59	P	Se-75	P
Ga-67	-	Sm-153	P
H-3	C	Sr-89	C
I-123	C	Sr-90	C
I-125	C	Tc-99	P+C
I-129	C	Tc-99m	P+C
I-131	C	Th-227	P
In-111	-	Th-228	P
In-113m	-	Th-230	P
K-40	C	Th-231	P
Kr-79	C	Th-232	P
Kr-81	C	Th-234	P
Kr-85	C	Tl-201	C
La-140	P	U-234	C
Mn-54	P	U-235	C
Mn-56	P	U-238	C
Mo-99	C+P	V-48	C+P
Na-22	C	Xe-133	-
Na-24	C	Y-90	P
Nb-94	P	Zr-95	P
Nb-95	P		

P = Particle reactive, i.e. binds to particles
C = Conservative, i.e. remains in solution
P+C = form will depend on environment (freshwater versus marine)
- = not stipulated, usually because of its short half-life.

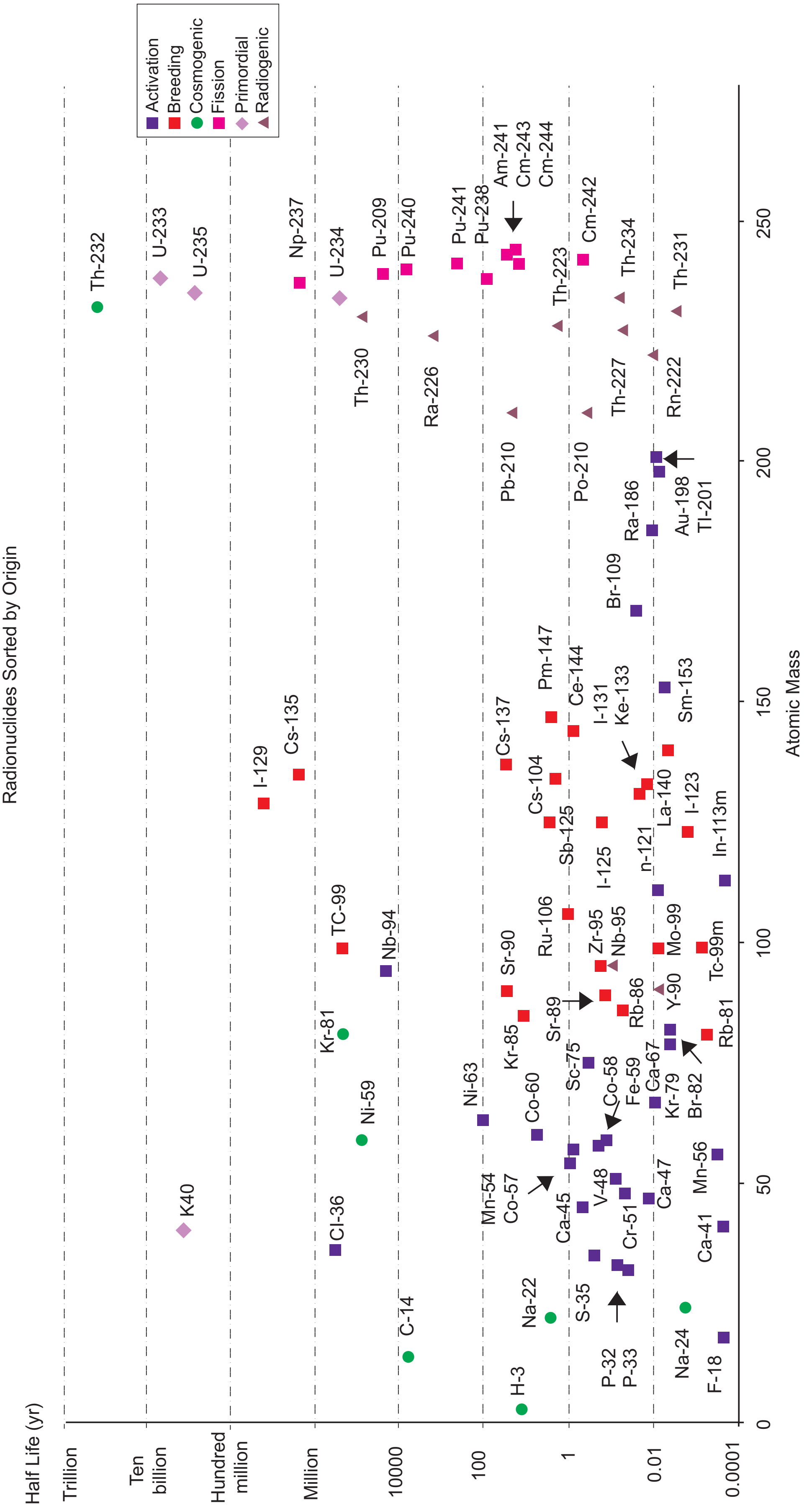


Figure 9: Origins of radionuclides

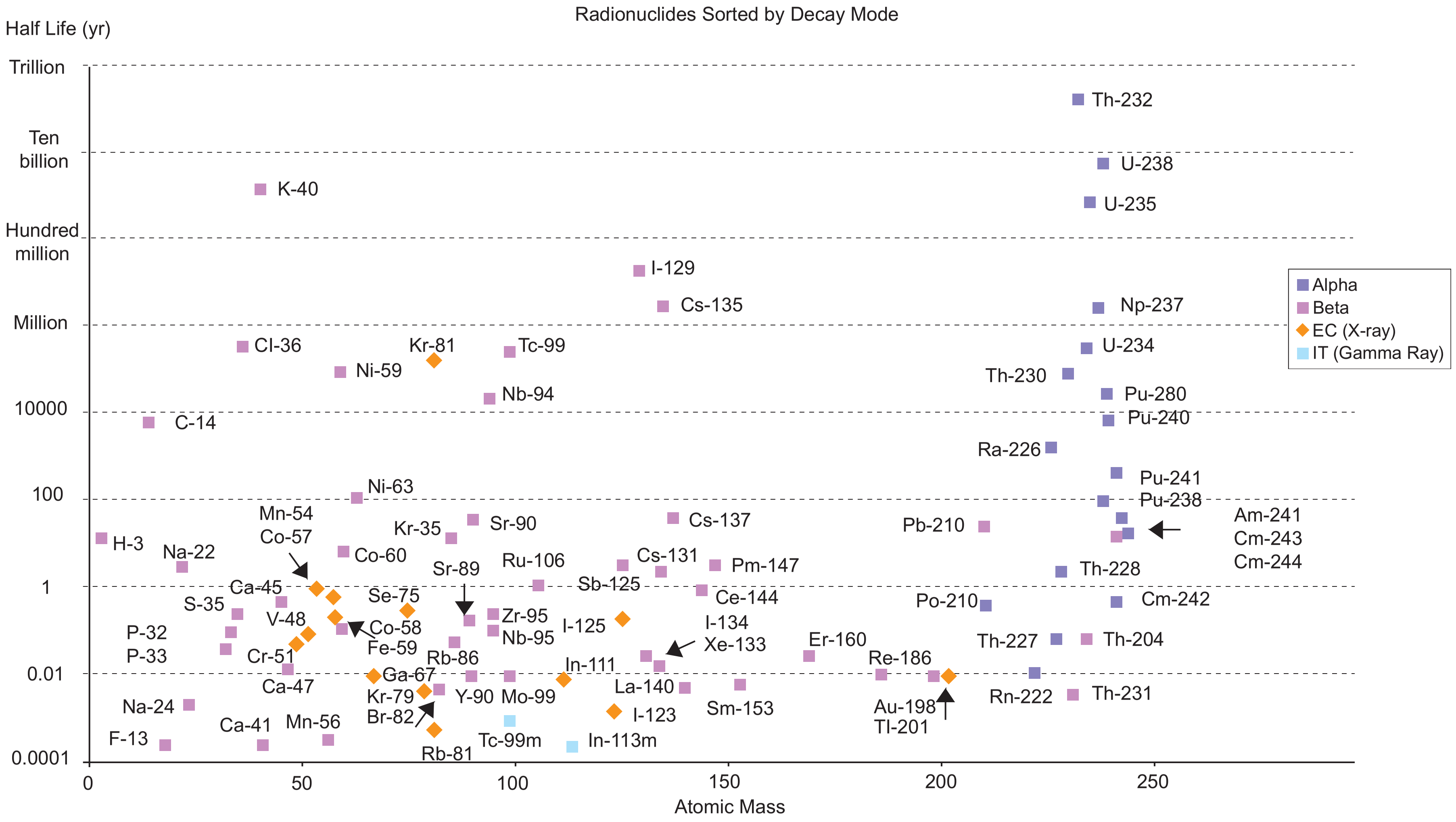


Figure 10: Main decay modes of radionuclides

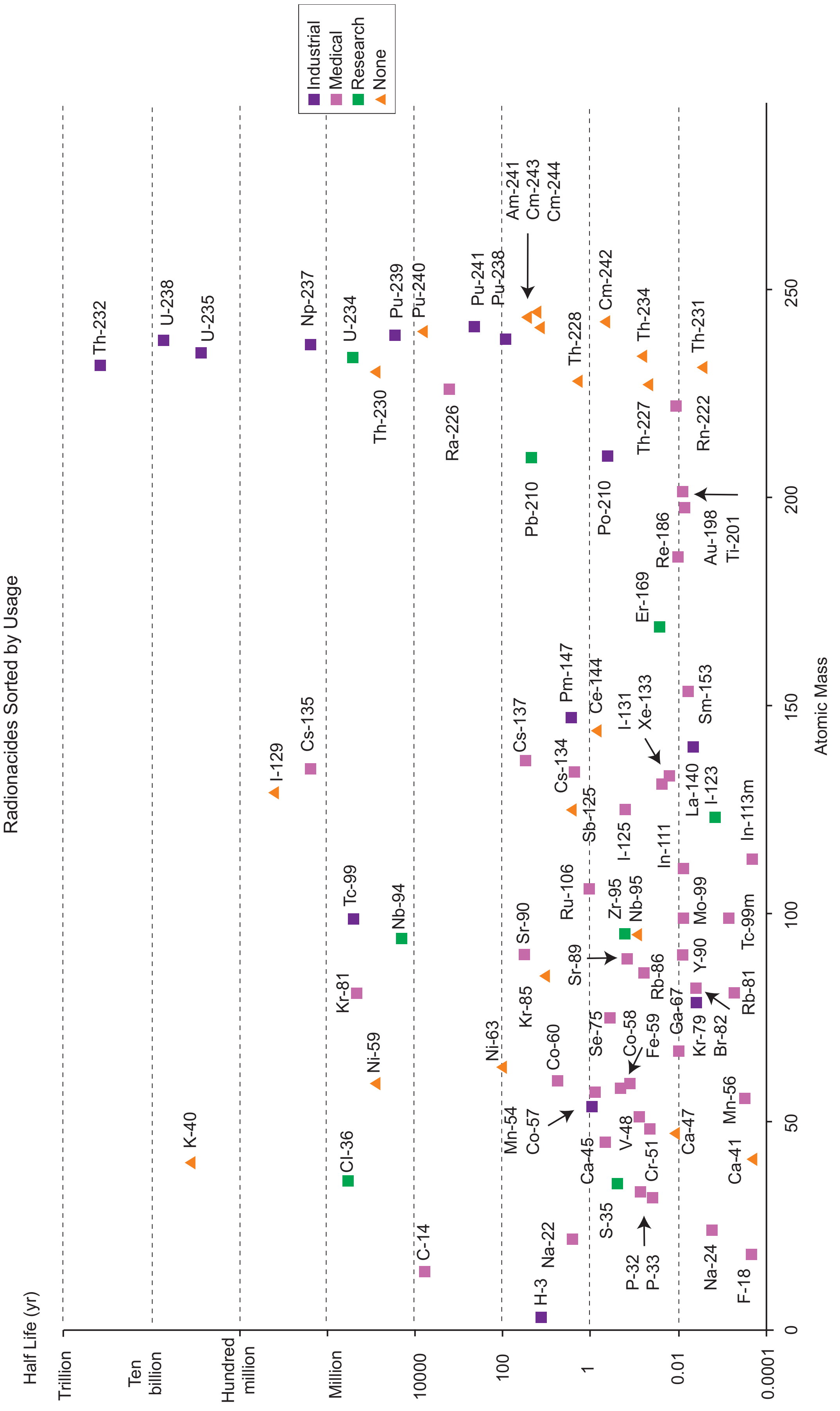


Figure 11: Main uses of radionuclides

5. References

Allott, R. and Dunn, M., 2001. Assessment of radioactive discharge screening levels for biota protected under the Habitats Regulations. Environment Agency NCAS Technical Report: NCAS/TR/2001/019. Environment Agency, Lancaster.

Copplestone D., Bielby S., Jones S.R., Patton D., Daniel P and Gize I., 2001. Impact assessment of ionising radiation on wildlife. Environment Agency R&D Publication 128. Environment Agency, Bristol.

Hill, G. and Holman, J.S., 2000. Chemistry in context, 5th edition. Nelson Thornes Cheltenham.

International Atomic Energy Agency (IAEA), 1994. Handbook of parameter values for the prediction of radionuclide transfer in temperate environments. IAEA Technical Reports Series No. 364. IAEA, Vienna.

International Atomic Energy Agency (IAEA), 2000. Safety glossary - terminology used in nuclear, radiation, radioactive waste and transport safety. IAEA version 1, April 2000. Available from http://www.iaea.org/ns/CoordiNet/index.htm (the CoordinNet page of Nuclear Safety).

International Commission on Radiological Protection (ICRP). Radionuclide transformations: energy and intensity of emissions, ICRP Publication 38. Annals of the ICRP, 11-13, 1983.

National Radiological Protection Board (NRPB), 1998. Living with radiation, 5th edition. NRPB, Chilton, Oxfordshire.

Strand, P., Beresford, N., Avila, R., Jones, S.R. and Larsson, C.-M. (editors), 2001. FASSET Deliverable D1: Identification of candidate reference organisms from a radiation exposure pathways perspective, FASSET Contract FIGE-CT-2000-00102. Available from http://www.fasset.org (go to the Results page).

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 1996. Sources and effects of ionizing radiation. 1996 Report to the General Assembly, with Annexes. United Nations, New York

United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 2000. Exposures to the public from man-made sources of radiation. 2000 Report to the General Assembly, Annex C. United Nations, New York.

Woodhead D. and Zinger I. (editors), 2003. FASSET Deliverable D4: Radiation effects to plants and animals, FASSET Contract No FIGE-CT-2000-00102. Available from http://www.fasset.org (go to the Results page).

Some useful websites:

http://nucleardata.nuclear.lu.se/nucleardata/toi/
Provides additional specialised information about the nuclear properties of radioactive isotopes

http://iaeand.iaea.or.at/formmird.html
Tables of nuclear and atomic radiation from nuclear decay and decay scheme drawings

http://www.fasset.org
FASSET (Framework for ASSessment of Environmental ImpacT) - an EC 5th Framework project which aims to develop a framework for the assessment of environmental impact of ionising radiation. Contract No FIGE-CT-2000-00102.

Additional reading

The following references provide additional (and sometimes more specialised) information about the radiological consequences of radioactivity to the environment and biota:

Publication	Content summary
Coughtrey P.J. et al. Radionuclide distribution and transport in terrestrial and aquatic ecosystems. Balkema, 1983-1985.	A six-volume work that provides a comprehensive review of environmental behaviour and characteristics of the elements.
ECORAD 2001. Proceedings of the International Congress, held Aix-en-Provence, France. IPSN France, 2001.	Proceedings of a conference to examine issues of the radioecology and ecotoxicology of continental and estuarine environments
Emsley, J. Nature's building blocks: An A-Z guide to the elements. Oxford University Press, 2001.	An introduction to the basic properties of the elements
IAEA. Protection of the environment from the effects of ionising radiation, IAEA-TECDOC-1091. Vienna, 2000.	An IAEA publication that discusses the various issues relating to the radiation protection of non-human species.
International Commission on Radiological Protection (ICRP). 1990 recommendations of the International Commission on Radiological Protection, ICRP Publication 60. Annals of the ICRP, 21(1-3), 1991.	Document currently being reviewed to specifically address the protection of the environment. Revision due in 2005.
Martin, A. An introduction to radiation protection, 4th edition. Chapman and Hall, 1996.	An introductory text that describes the basic concepts of radiation and how systems of radiation protection can be developed.
Nuclear Energy Agency/Organisation for Economic Co-operation and Development (NEA/OECD). Radiological protection of the environment: the path forward to a new policy? Workshop Proceedings, held Taormina, Sicily, Italy, 12-14 February 2002.	The proceedings of a conference that looked at the issues associated with developing a system of radiation protection for the environment.
Pentreath, R,J. A system for radiological protection of the environment: some initial thoughts and ideas. J. Radiol. Prot., 19, 117-128, 1999.	A discussion of the issues relating to protection of the environment, including the notion that protection of individuals may be as important as protection of populations.
Thorne, M.C. et al. A model for evaluating radiological impacts on organisms other than man for use in post-closure radiological assessments of geological repositories for radioactive wastes. J Radiol. Prot. 22(3), 249-277, 2002.	A paper that proposes a model for use in estimating radiological doses to non-human species from radionuclides originating in geological waste repositories.
Van der Stricht, E. and Kirchmann, R. (editors). Radioecology: radioactivity and ecosystems. Fortemps Drukkerij, LiËge, Belgium, 2001.	An introduction to radioecology - intended as a learning textbook, not a summary of the latest research findings.

PART 2

Information on each radionuclide - listed by symbol

Symbol	Radionuclide	Page	Symbol	Radionuclide	Page
Am-241	Americium-241	30	Kr-85	Krypton-85	100
Ar-41	Argon-41	32	La-140	Lanthanum-140	102
Au-198	Gold-198	34	Mn-54	Manganese-54	104
Br-82	Bromine-82	36	Mn-56	Manganese-56	106
C-11	Carbon-11	38	Mo-99	Molybdenum-99	108
C-14	Carbon-14	40	Na-22	Sodium-22	110
Ca-45	Calcium-45	42	Na-24	Sodium-24	112
Ca-47	Calcium-47	44	Nb-94	Niobium-94	114
Ce-144	Cerium-144	46	Nb-95	Niobium-95	116
Cl-36	Chlorine-36	48	Ni-59	Nickel-59	118
Cm-242	Curium-242	50	Ni-63	Nickel-63	120
Cm-243	Curium-243	52	Np-237	Neptunium-237	122
Cm-244	Curium-244	54	O-15	Oxygen-15	124
Co-57	Cobalt-57	56	P-32	Phosphorus-32	126
Co-58	Cobalt-58	58	P-33	Phosphorus-33	128
Co-60	Cobalt-60	60	Pa-234m	Protactinium-234m	130
Cr-51	Chromium-51	62	Pm-147	Promethium-147	132
Cs-134	Caesium-134	64	Po-210	Polonium-210	134
Cs-135	Caesium-135	66	Pb-210	Lead-210	136
Cs-137	Caesium-137	68	Pu-238	Plutonium-238	138
Depleted uranium		70	Pu-239	Plutonium-239	140
Er-169	Erbium-169	72	Pu-240	Plutonium-240	142
F-18	Fluorine-18	74	Pu-241	Plutonium-241	144
Fe-59	Iron-59	76	Ra-226	Radium-226	146
Ga-67	Gallium-67	78	Rb-81	Rubidium-81	148
H-3	Tritium	80	Rb-86	Rubidium-86	150
I-123	Iodine-123	82	Re-186	Rhenium-186	152
I-125	Iodine-125	84	Rn-222	Radon-222	154
I-129	Iodine-129	86	Ru-106	Ruthenium-106	156
I-131	Iodine-131	88	S-35	Sulphur-35	158
In-111	Indium-111	90	Sb-125	Antimony-125	160
In-113m	Indium-113m	92	Se-75	Selenium-75	162
K-40	Potassium-40	94	Sm-153	Samarium-153	164
Kr-79	Krypton-79	96	Sr-89	Strontium-89	166
Kr-81	Krypton-81	98	Sr-90	Strontium-90	168

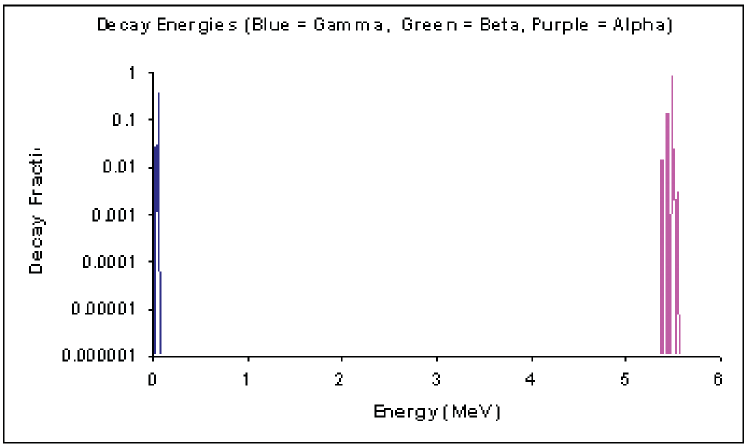
Symbol	Radionuclide	Page	Symbol	Radionuclide	Page
Tc-99	Technetium-99	170	Total alpha		188
Tc-99m	Technetium-99m	172	Total beta		189
Th-227	Thorium-227	174	U-234	Uranium-234	190
Th-228	Thorium-228	176	U-235	Uranium-235	192
Th-230	Thorium-230	178	U-238	Uranium-238	194
Th-231	Thorium-231	180	V-48	Vanadium-48	196
Th-232	Thorium-232	182	Xe-133	Xenon-133	198
Th-234	Thorium-234	184	Y-90	Yttrium-90	200
Tl-201	Thallium-201	186	Zr-95	Zirconium-95	202

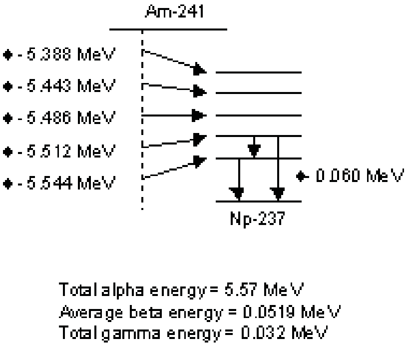
Name	Americium-241	*Symbol*	Am-241	*Origin*	Breeding
Radioactive half-life	432 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Pu-241	*Daughter*	Np-237 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Formed by neutron activation of uranium in a nuclear reactor, followed by decay of the activation products
Uses		• As an alpha radiation source in smoke detectors
Modes of release	Land	• Deposition to soils as a result of historic weapons testing • Releases from nuclear reactors or reprocessing plants
	Air	• Releases due to weapons testing • Releases from nuclear reactors or experimental facilities
	Water	• Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The most important oxidation state of americium in solution is +3, with carbonate expected to be the dominant form. The solubility is expected to increase as pH increases. Americium compounds hydrolyse in water, often accompanied by colloid formation.	The higher actinides Am and Cm have very similar chemical, biochemical and biogeochemical characteristics. However, Am has been more extensively studied than Cm, so it is more appropriate to regard Am as an analogue for Cm than vice versa.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Am-241 deposited in the terrestrial environment will mainly be transferred to soils. Am-241 is highly particle reactive and therefore binds strongly to soils and sediments.	Am-241 is highly particle reactive in the aquatic environment and therefore tends to accumulate in sediments. Transport of Am-241 in aquatic systems (e.g. saltmarsh) will therefore be determined by sediment transport therein.	Am-241 is expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its high particle reactivity, Am-241 will tend to remain in soil systems on a timescale of decades to centuries. Losses from the soil systems may occur by erosion. In aquatic systems, sediments are the most likely environmental sink and Am-241 migration will be closely associated with sediment transport.	Because of its high particle reactivity, Am-241 has a low bioavailability to plants. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation. It is also not very available to animals - uptake from the gastrointestinal tract is limited (<0.1 %), but the liver and skeleton would act as sinks for Am-241.

Effects on organisms

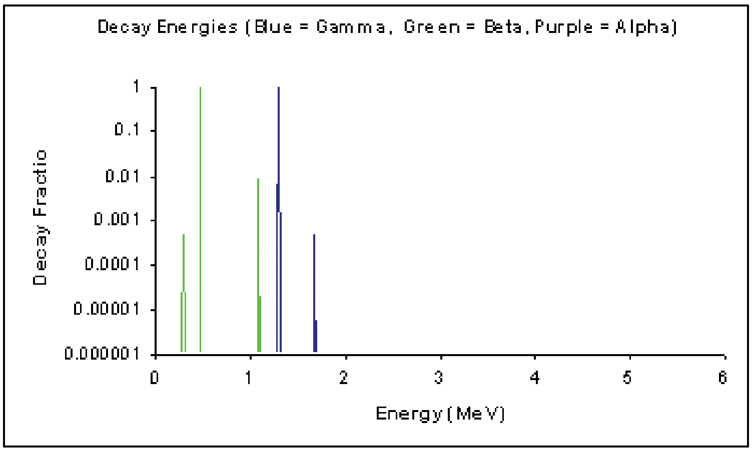
Dose effects/dosimetry	Species-specific considerations
Am-241 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence.	Therefore, Am-241 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation. Specific consideration should be given to molluscs, crustaceans and aquatic plants, for which concentration factors can be a factor of 1,000 or more higher than the surrounding water.

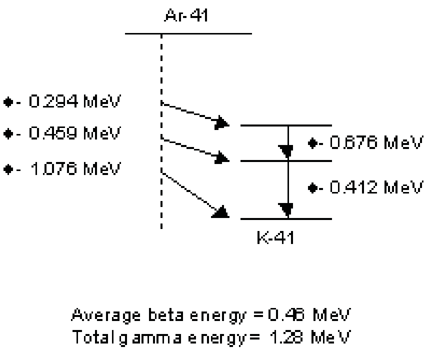
Name	Argon-41	*Symbol*	Ar-41	*Origin*	Activation
Radioactive half-life	109 minutes	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	K-41	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of stable potassium-41 and argon-40 in gas-cooled nuclear reactors
Uses		• No significant uses outside research activities
Modes of release	Land	• Not generally released to land
	Air	• During venting of coolant gas in gas-cooled nuclear reactors
	Water	• Not generally released to water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Argon is a noble gas (it has a completely filled outer electron shell). It forms only a limited number of chemical compounds due to its lack of reactivity.	All the noble gases (Ne, Ar, Kr, Xe and Rn) exhibit similar environmental behaviour. Rn is a special case because it is generated in the environment from isotopes of radium and because it decays to produce chemically reactive, short-lived and long-lived radioactive progeny. For this reason, Rn should not be used as a dosimetric analogue for Ar.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ar-41 is not readily transferred to the terrestrial environment.	Ar-41 is not transferred significantly to the aquatic environment.	Ar-41 is almost exclusively released to the atmosphere. Its very short radioactive half-life and low reactivity means that it decays almost entirely during atmospheric transport and is not transferred significantly to other environmental media.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
No major sink, owing to its lack of reactivity and very short half-life.	Ar-41 is sparingly soluble in body tissues, notably those with a high fat content. However, it is not metabolised. Some Ar-41 will be present in the lungs in inhaled air.

Effects on organisms

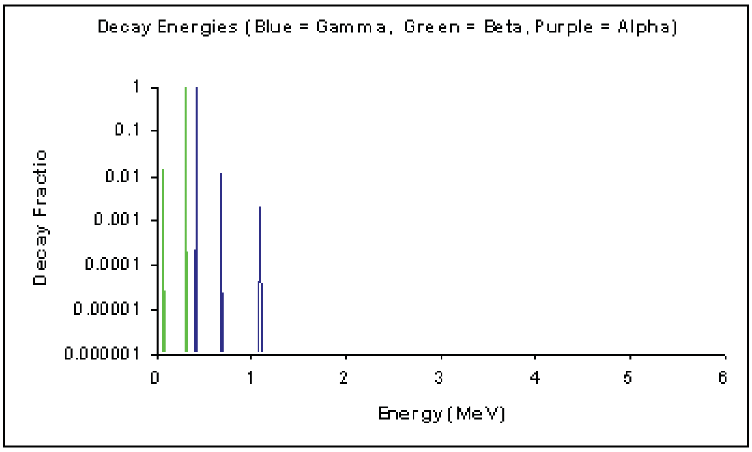
Dose effects/dosimetry	Species-specific considerations
Ar-41 emits energetic gamma rays. Radiation doses to organisms arise mainly due to external irradiation.	Because the main consideration is external irradiation, there are no major species-dependent considerations. Aquatic organisms, plant roots and burrowing animals will be shielded, to a greater or lesser degree, from such exposures.

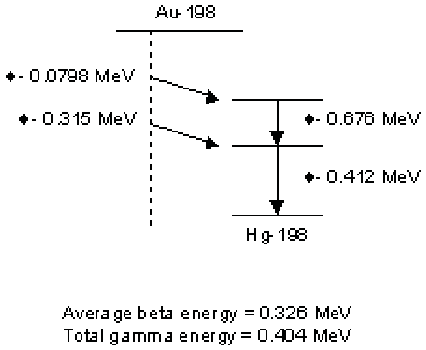
Name	Gold-198	*Symbol*	Au-198	*Origin*	Activation
Radioactive half-life	2.7 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Hg-198	*Detection*	In situ

Production, uses and modes of release

Production		• Produced by irradiating stable isotopes with neutrons or protons in a nuclear reactor or cyclotron
Uses		• Used in the treatment of brain tumours and ovarian cancer
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Could be released to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Gold is an element of the series IB metals. It shows four oxidation states (+5, +3, +2 and +1); the most common are +3 and +1. Gold forms a number of organometallic compounds, as well as compounds with the halides and oxygen. Cyanide increases the solubility of gold and its salts and complexes.	No analogue elements have been identified.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Au-198 is not expected to be very mobile in the environment.	Au-198 is likely to be particle reactive. It is expected to decay substantially during its transport through the aquatic system.	Releases of aerosols to the atmosphere could occur during production or use. Deposition of Au-198 is likely to be limited on account of its short half-life.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Au-198 in the terrestrial environment will remain in situ, either on the external surfaces of plants or on the underlying soil. In aquatic systems, bottom sediments are the most likely environmental sink and Au-198 migration will be closely associated with sediment transport.	Ingestion of Au-198 might occur by soil fauna and herbivores. In mammals, gold is moderately well absorbed from the gastrointestinal tract. It then becomes rapidly and relatively uniformly distributed throughout all organs and tissues. Plants that metabolise cyanide absorb most gold, as the cyanide helps to solubilise the gold. Such plants include horsetails, Douglas fir, honeysuckle and Indian mustard (Brassica juncea).

Effects on organisms

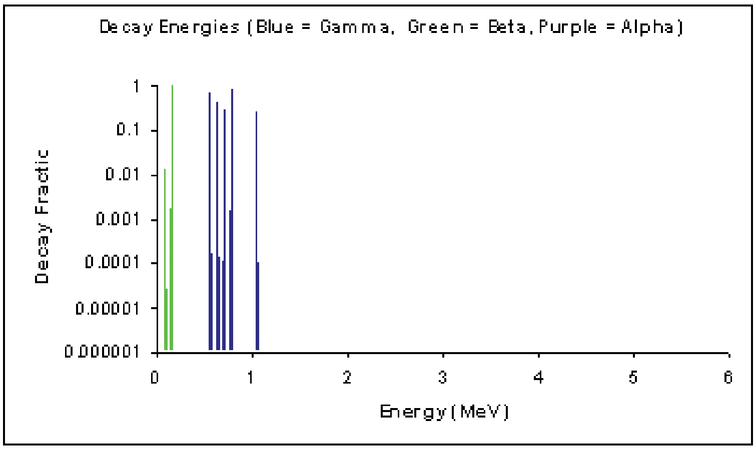
Dose effects/dosimetry	Species-specific considerations
Au-198 is a mixed beta-gamma emitter. External exposure would be significant. It would give rise to whole-body exposures from the gamma component and superficial exposures from the beta component. Uptake in animals would give a significant beta-gamma component from internal exposure.	In mammals, the rapidity of urinary excretion could result in doses to the wall of the urinary bladder being substantially larger than those to other organs and tissues. For plants, consideration needs to be given to vegetation types (e.g. stands of trees) that could intercept a substantial fraction of the dispersing plume.

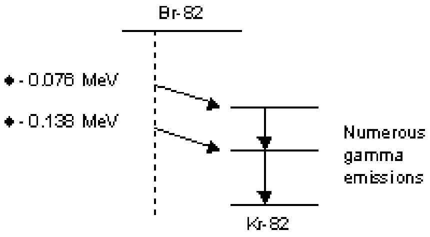
Name	Bromine-82	*Symbol*	Br-82	*Origin*	Activation
Radioactive half-life	35.3 hours	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Kr-82	*Detection*	In situ

Production, uses and modes of release

Production		• Produced by irradiating stable isotopes with neutrons or protons in a nuclear reactor or cyclotron
Uses		• Used as a tracer for exchangeable chloride and for measurements of extracellular fluid properties
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Could be released to sewers

Decay modes





Average beta energy = 0.138 MeV
Total gamma energy = 2.63 MeV

Chemical properties/characteristics

Speciation	Analogue species
Bromine is a halogen element that shows a predominant oxidation state of -1. It is very reactive and forms bromide compounds with many other elements. It also forms a series of bromate compounds involving bromine and oxygen.	Chlorine is the most appropriate analogue. However, as chlorine is an essential element for all plants and animals and bromine is not, this analogy should be used with caution.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Bromide is not particle reactive and so may be expected to move freely through the terrestrial environment. The very short half-life will limit the extent to which it can migrate in the terrestrial environment.	Bromide will behave conservatively in aquatic systems. The very short half-life will limit the extent to which it can migrate in the terrestrial environment.	Br-82 could be released to the atmosphere. It is dispersed either as a reactive vapour or an aerosol, but the very short half-life may prevent wet and dry deposition. Br-82 in bromide also reacts with atmospheric oxygen.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Br-82 will either decay in situ (if it is retained in plants or taken up by animals) or it will decay as it disperses in surface waters and groundwaters.	Plants can take up Br-82 by direct foliar absorption, after which it is dispersed relatively uniformly throughout their tissues. Plants may also take up bromide through their roots, via soil water. Animals will take up Br-82 from plants and water bodies. Bromine is essentially completely absorbed from the gastrointestinal tract of mammals and is relatively uniformly distributed throughout all organs and tissues of the body. Br-82 is highly bioavailable to aquatic organisms, namely aquatic plants. The very short half-life of Br-82 will limit the accumulation process.

Effects on organisms

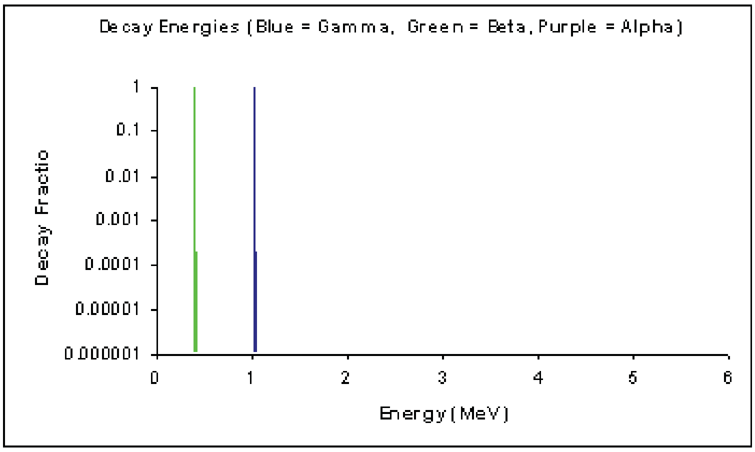
Dose effects/dosimetry	Species-specific considerations
Br-82 is a beta emitter and, in addition, a strong emitter of energetic gamma rays. Organisms will be subjected to external irradiation from gamma rays, and gamma rays from internally incorporated Br-82. The beta particle will also make a small contribution to dose.	Br-82 is thought to be highly bioavailable to a wide range of plant and animal species.

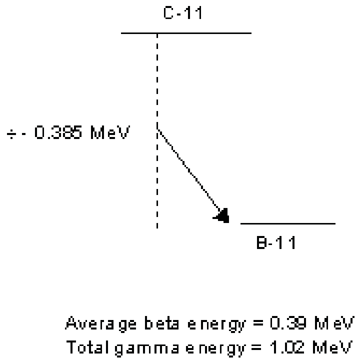
Name	Carbon-11	*Symbol*	C-11	*Origin*	Activation
Radioactive half-life	20 minutes	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	B-11	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced by irradiating stable isotopes with neutrons or protons in a nuclear reactor or cyclotron
Uses		• Labelling of organic compounds in biomedical studies
Modes of release	Land	• Sewage sludge application to land, but would probably decay away long before this can occur
	Air	• Not generally released to air
	Water	• Could be released to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The majority of compounds of carbon are in the +4 oxidation state. Its chemistry is characterised by its tendency to form stable bonds with oxygen, hydrogen, halides, nitrogen, sulphur and other carbon atoms. In solution, the carbonate and bicarbonate ions predominate.	Because of its fundamental role in biochemistry and biogeochemistry, there are no other elements that can be considered as environmental analogues of carbon. However, studies of stable carbon behaviour in the environment and of distinctions in behaviour of its two stable isotopes (C-12 and C-13) provide important insights into the environmental behaviour of radioactive isotopes of carbon.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
The very short radioactive half-life of C-11 precludes significant transport in terrestrial environments.	The very short radioactive half-life of C-11 precludes significant transport in aquatic environments.	The very short radioactive half-life of C-11 precludes significant transport in atmospheric environments.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Almost all C-11 will be lost by radioactive decay during its dispersion from the source. Almost all that is taken up by plants will decay at the site of photosynthesis. C-11 that is taken up by animals will rapidly become relatively uniformly distributed throughout the body and decay in situ.	There is a limited potential for uptake into plants for photosynthesis and into animals by respiration following an atmospheric release. There is little possibility of significant intake and uptake following an aquatic release.

Effects on organisms

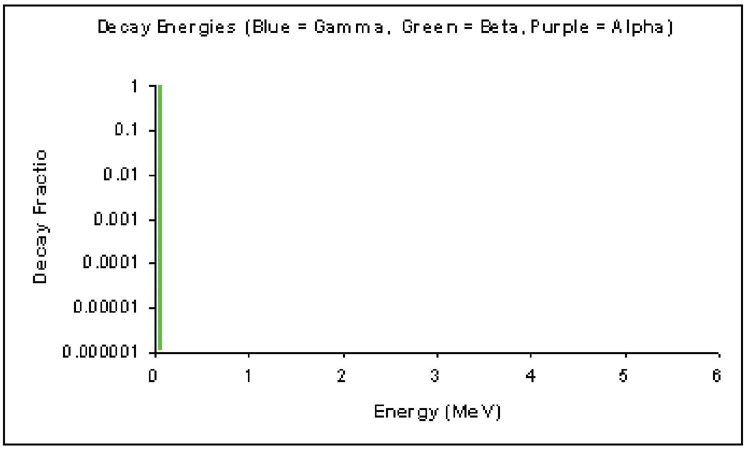
Dose effects/dosimetry	Species-specific considerations
C-11 emits positrons. These, in turn, generate annihilation radiation in the form of 0.511 MeV photons. Uptake into plants could give rise to irradiation by both beta and gamma radiation. This irradiation would be expected to be mainly of above ground parts. Internal irradiation of animals would also be from beta and gamma irradiation from C-11 distributed reasonably uniformly throughout all organs and tissues of the body.	No specific issues on account of the very short half-life of C-11.

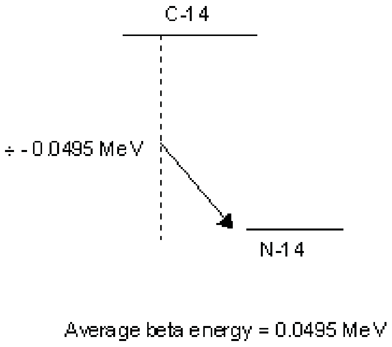
Name	Carbon-14	*Symbol*	C-14	*Origin*	Cosmogenic
Radioactive half-life	5,730 years	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	N/A	*Daughter*	N-14	*Detection*	Laboratory

Production, uses and modes of release

Production		• Naturally in the upper atmosphere due to cosmic ray interactions • In nuclear reactors by neutron irradiation of carbon and nitrogen
Uses		• Radiocarbon dating • Diagnostic medical procedures (e.g. studies of gigantism)
Modes of release	Land	• Deposition of fallout from a nuclear accident or natural processes
	Air	• Naturally present through cosmic ray interactions • Historic weapons testing
	Water	• Transfer from atmosphere to shallow and deep ocean waters • Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The majority of compounds of carbon are in the +4 oxidation state. Its chemistry is characterised by its tendency to form stable bonds with oxygen, hydrogen, halides, nitrogen, sulphur and other carbon atoms. In solution, the carbonate and bicarbonate ions predominate.	Because of its fundamental role in biochemistry and biogeochemistry, there are no other elements that can be considered as environmental analogues of carbon. However, studies of stable carbon behaviour in the environment and of distinctions in behaviour of its two stable isotopes (C-12 and C-13) provide important insights into the environmental behaviour of radioactive isotopes of carbon.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
C-14 is rapidly dispersed through terrestrial environments by a wide variety of biological, biochemical and biogeochemical processes. For disperse sources, this results in similar specific activities for different components of the environment.	C-14 is rapidly dispersed through aquatic environments.	C-14 is mainly released to, or produced in, the atmosphere. It then becomes globally dispersed on a timescale of months to a few years, i.e. very much shorter than its radioactive half-life.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Long-term sinks are deep ocean waters and the deposition of carbonaceous sediments. On shorter time scales, biota can constitute a sink or source, depending on whether the amount of standing biomass is increasing or decreasing.	Plants take up C-14 mainly for photosynthesis (and lose it by respiration as carbon dioxide). However, a limited degree of root uptake also occurs and a few percent of plant carbon can derive from the soil rather than the above ground atmosphere. Animals are mainly exposed to C-14 by ingestion. In the short-term, uptake will be highest in metabolically active tissues, but this tends to be compensated for in the longer term by higher rates of turnover in such tissues.

Effects on organisms

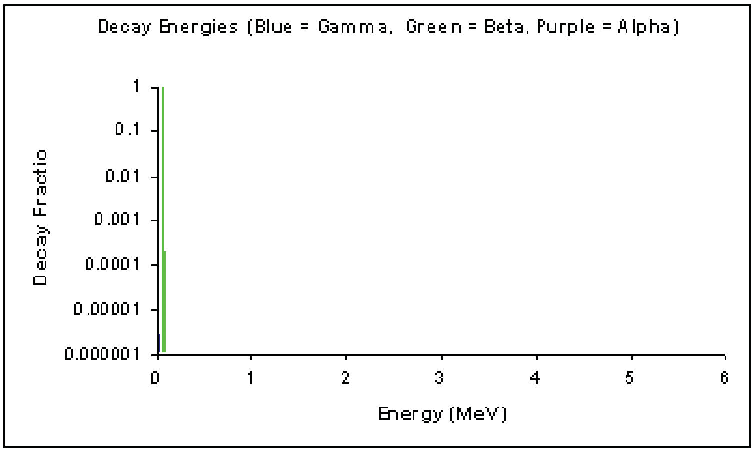
Dose effects/dosimetry	Species-specific considerations
C-14 is a soft beta emitter that becomes relatively uniformly distributed throughout all organs and tissues in both plants and animals. Because it is a pure soft beta emitter, dose rates are entirely determined by concentrations near the point of exposure.	If localised releases occur to freshwaters with small dilution volumes or flow rates, specific consideration should be given to the very high degree of uptake that can occur in fish (IAEA, 1994).

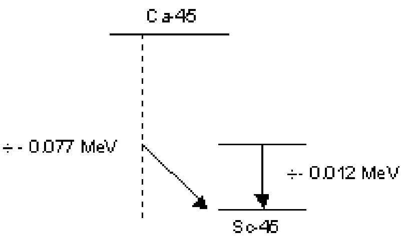
Name	Calcium-45	*Symbol*	Ca-45	*Origin*	Activation
Radioactive half-life	163 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Sc-45	*Detection*	Laboratory

Production, uses and modes of release

Production		• Neutron irradiation of stable precursors in a cyclotron or nuclear reactor
Uses		• Used in medicine as a tracer to investigate calcium metabolism
Modes of release	Land	• Sewage sludge application to land.
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Average beta energy = 0.077 MeV
Total gamma energy = 4.4 10^{-8} MeV

Chemical properties/characteristics

Speciation	Analogue species
Calcium is an alkaline earth element and, as consequence, the most important species is the Ca^{2+} ion. Isotopes of calcium can therefore be expected to take part in a number of precipitation and substitution reactions. Precipitation as sulphate or carbonate is possible.	Sr is a close chemical analogue. Although Ca is an essential element for almost all biota, the extensive studies of Sr-90 in the environment can sometimes provide useful information about the chemistry, biochemistry and biogeochemistry of Ca.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ca-45 deposited to soils is expected to be relatively mobile and thus available for uptake by plants.	Ca-45 can exhibit a relatively high degree of sorption to aquatic sediments and aquatic transport will thus be governed by movement of sediments.	If released to the atmosphere, Ca-45 would be present as an aerosol. Atmospheric transport would result in wet and dry deposition to plants and soils.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The relatively short half-life of Ca-45 means that it is likely to decay close to its site of deposition in terrestrial environments. Substantial dispersion is likely in aquatic environments, with decay either in the water column or in deposited sediments.	Ca-45 is moderately bioavailable to plants. Foliar uptake can be significant. Calcium is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~30 %. It will be translocated mainly to mineral bone, skeleton and carapace. Concentrations in soft tissues are likely to be at least two orders of magnitude lower than concentrations in bone. The bioavailability of Ca to animals is high (fractional gastrointestinal absorption ~30 %). Concentrations of Ca will be low for marine fish, but can be quite high for freshwater fish and marine invertebrates.

Effects on organisms

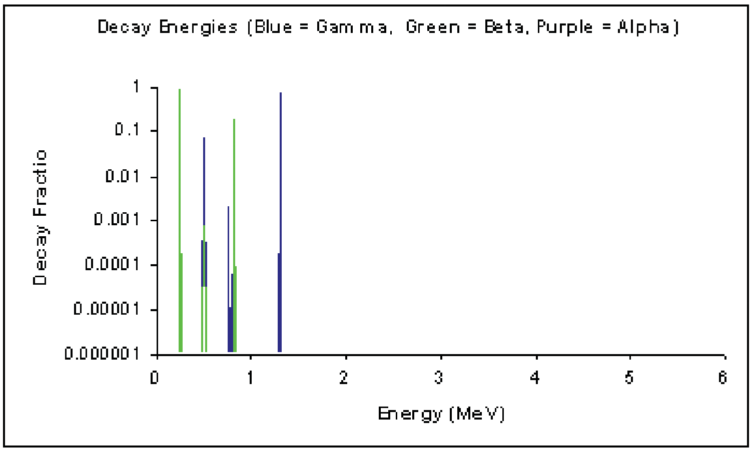
Dose effects/dosimetry	Species-specific considerations
Ca-45 is a soft beta emitter. Therefore, only internal irradiation is relevant. Relatively high doses will occur to cells embedded in, or present on the surfaces of, mineralised tissues.	Discharges to freshwaters should be given specific consideration because of the high concentration ratios appropriate to freshwater fish.

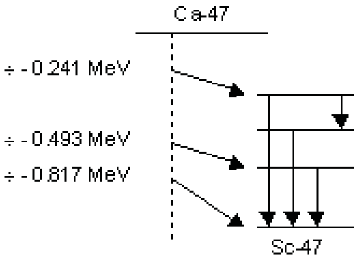
Name	Calcium-47	*Symbol*	Ca-47	*Origin*	Activation
Radioactive half-life	163 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Sc-47 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Activation of stable calcium-46 by neutrons in nuclear reactors
Uses		• No significant uses outside research activities
Modes of release	Land	• Not generally released to land
	Air	• Not generally released to air
	Water	• Not generally released to water

Decay modes





Average beta energy = 0.345 MeV
Total gamma energy = 1.06 MeV

Chemical properties/characteristics

Speciation	Analogue species
Calcium is an alkaline earth element and, as consequence, the most important species is the Ca^{2+} ion. Isotopes of calcium can therefore be expected to take part in a number of precipitation and substitution reactions. Precipitation as sulphate or carbonate is possible.	Sr is a close chemical analogue. Although Ca is an essential element for almost all biota, the extensive studies of Sr-90 in the environment can sometimes provide useful information about the chemistry, biochemistry and biogeochemistry of Ca.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ca-47 added to soils is expected to be relatively mobile and thus available for uptake by plants.	Ca-47 can exhibit a relatively high degree of sorption to aquatic sediments and aquatic transport will thus be governed by movement of sediments.	If released to the atmosphere, Ca-47 would be present as an aerosol. Atmospheric transport would result in wet and dry deposition to plants and soils.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The short half-life of Ca-47 means that it is likely to decay close to its site of deposition in terrestrial environments. Substantial dispersion is likely in aquatic environments, with decay either in the water column or in deposited sediments.	Ca-47 is moderately bioavailable to plants. Foliar uptake can be significant. Calcium is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~30 %. It will be translocated mainly to mineral bone, skeleton and carapace. Because of its short half-life, only limited accumulation in bone is expected. The bioavailability of Ca to animals is high (fractional gastrointestinal absorption ~30 %). Concentrations of Ca will be low for marine fish, but can be quite high for freshwater fish and marine invertebrates.

Effects on organisms

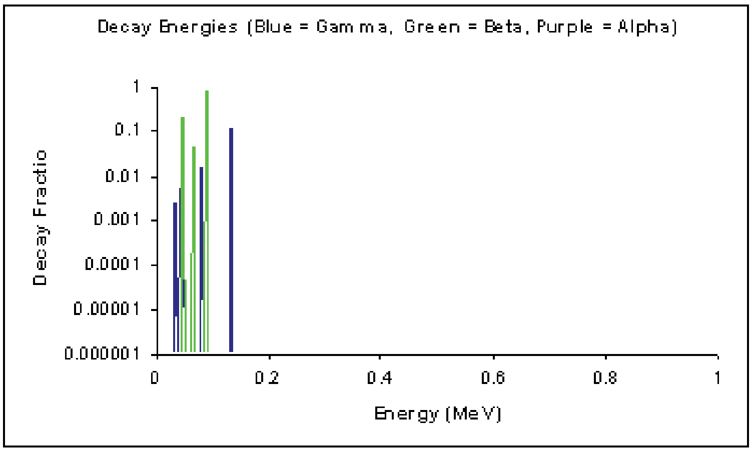
Dose effects/dosimetry	Species-specific considerations
Ca-47 is a mixed beta-gamma emitter. External irradiation from the plume or initial terrestrial deposits may be more important than internal uptake by terrestrial biota because of the short half-life of the radionuclide.	No special considerations on account of the short half-life of Ca-47.

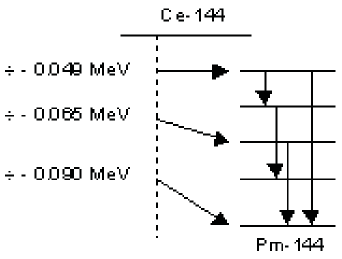
Name	Cerium-144	*Symbol*	Ce-144	*Origin*	Fission
Radioactive half-life	285 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Pr-144 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• No significant uses outside research activities
Modes of release	Land	• During treatment and disposal of spent fuel
	Air	• During treatment and disposal of spent fuel
	Water	• During treatment and disposal of spent fuel • Liquid discharges from nuclear facilities

Decay modes





Average beta energy = 0.091 MeV
Total gamma energy = 0.021 MeV

Chemical properties/characteristics

Speciation	Analogue species
Cerium is a rare-earth element that shows oxidation states of +3 and +4. As such, cerium forms compounds with hydrogen, oxygen and the halides. It also forms stable complexes.	The rare earth elements (Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) exhibit similar chemical, biochemical and biogeochemical characteristics. However, these characteristics change systematically in the group with increasing atomic number. Cerium is one of the best-studied members of the group. Analogies with other members of the group and with higher actinides such as Am can be useful.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ce-144 is highly particle reactive and hence would remain bound to soil particles and on the surfaces of plants. Transfers from plant to soil and bulk movement of soils would be the main transport mechanisms.	Ce-144 is highly particle reactive. It is likely to bind to suspended sediments.	If released to the atmosphere, Ce-144 would be present as an aerosol, probably as the oxide. Atmospheric transport would result in wet and dry deposition to plants and soils.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The relatively short half-life and high particle reactivity of Ce-144 mean that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, bottom sediments close to the source of release may form an important sink.	Ce-144 is not very bioavailable to animals. The fractional gastrointestinal absorption is typically <0.1 %. Any Ce-144 that is absorbed is mainly deposited in the liver and skeleton. Intake by terrestrial animals is likely to be mainly by ingestion of Ce-144 present on the exterior surfaces of plants or deposited on soil. Very little uptake from the gastrointestinal tract is anticipated, except perhaps in pre-weaned animals. In the aquatic environment, uptake by fish and invertebrates is mainly direct from the water rather than from food. Uptake by aquatic plants is likely to be by surface adsorption.

Effects on organisms

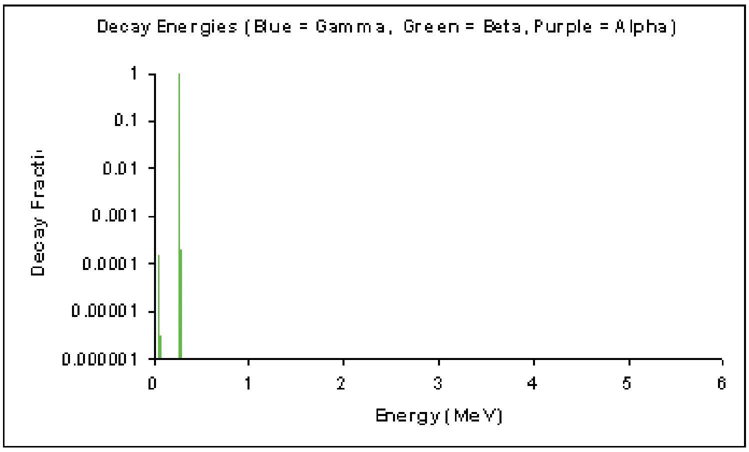
Dose effects/dosimetry	Species-specific considerations
Ce-144 is a mixed beta-gamma emitter. External irradiation from activity deposited in the terrestrial environment could be of greater importance than internal exposure.	In mammals and birds, the walls of the gastrointestinal tract are likely to receive substantially higher doses than other organs and tissues. This is due to irradiation by unabsorbed Ce-144 passing through the tract.

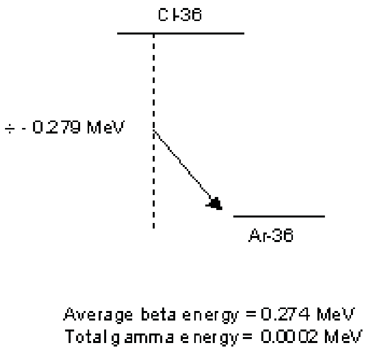
Name	Chlorine-36	*Symbol*	Cl-36	*Origin*	Cosmogenic
Radioactive half-life	3.01 x 105yrs	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	N/A	*Daughter*	Ar-36	*Detection*	Laboratory

Production, uses and modes of release

Production		• Cosmic ray interactions in the upper atmosphere • Neutron irradiation of residual chlorine in reactor graphite rods
Uses		• Radiological dating of sediment and glacial deposits
Modes of release	Land	• Treatment and disposal of spent fuel and reactor hardware
	Air	• Treatment and disposal of spent fuel and reactor hardware
	Water	• Treatment and disposal of spent fuel and reactor hardware

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Chlorine is a halogen element. It shows an oxidation state of -1 in chloride compounds, and states of +1 and others in chlorate compounds (these contain chlorine and oxygen). In environmental situations, the chloride species are of greatest importance.	There are chemical similarities between F, Cl, Br and I. However, the biochemical roles and behaviour of these elements are very different. The only chemical analogue to Cl-36 is perhaps the stable Cl element.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cl-36 is of greatest interest when it contaminates soils. It exhibits the highest plant:soil concentration ratio of any radionuclide. In contaminated soils, the majority of the Cl-36 may have been translocated to plants within a few weeks.	Cl-36 is highly conservative in waters and is, therefore, readily transported through the aquatic environment. It may be rapidly dispersed in water bodies or enter the soil system.	If released to atmosphere, Cl-36 would be expected to be widely dispersed and readily bioavailable to both plants and animals.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Cl-36 disperses into the large pool of stable chloride that is present in the environment. As chloride is mobile in groundwaters and surface waters, the Cl-36 will tend to migrate in the long-term to the marine environment and disperse throughout the worldís oceans.	Cl-36 is highly accumulated by plants from soils. Cl-36 present in this plant material is then highly bioavailable to animals. These terrestrial foodchain pathways are thought to be of greater importance than aquatic pathways due to the rapid dilution and dispersion of Cl-36 in surface waters and the limited degree of concentration even by freshwater organisms.

Effects on organisms

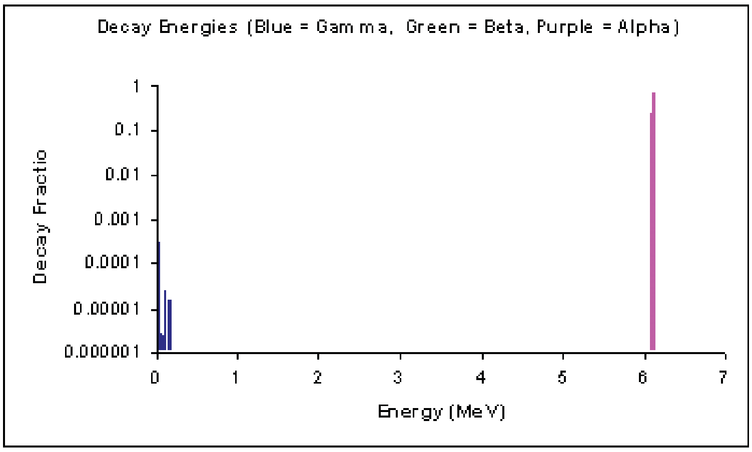
Dose effects/dosimetry	Species-specific considerations
Cl-36 is a pure beta emitter. It is relatively uniformly distributed throughout plant and animal body tissues. For dosimetric purposes, it is often useful to adopt a specific activity model in which the ratio of Cl-36 to stable chlorine is assumed to be the same in source and receptor components of the environment.	No major species-specific considerations arise because chlorine is ubiquitously present in plant and animal tissues, and is relatively uniformly distributed throughout them.

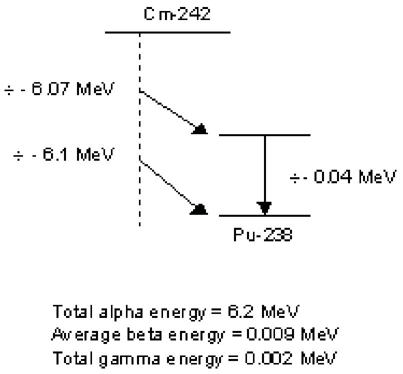
Name	Curium-242	*Symbol*	Cm-242	*Origin*	Breeding
Radioactive half-life	163 days	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Am-242	*Daughter*	Pu-238 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Successive capture of neutrons by plutonium and americium in a nuclear reactor, followed by decay of the products
Uses		• Source of power in satellites and other space equipment • Source of alpha particles for analysis of moon surface
Modes of release	Land	• Deposition following atmospheric testing of nuclear weapons • As a result of nuclear accidents and releases from nuclear facilities
	Air	• Atmospheric testing of nuclear weapons
	Water	• Leaching from soils to groundwater

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Most curium compounds are based on an oxidation state of +3. For example, it forms trihalide compounds (e.g. CmF_3), although compounds such as CmO_2 are examples of the +4 oxidation state. Curium and its compounds are capable of the formation and precipitation of colloids and organic complexes.	The two higher actinides, Am and Cm, have very similar chemical, biochemical and biogeochemical characteristics. However, Am has been more extensively studied than Cm, so it is appropriate to regard Am as an analogue for Cm.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cm-242 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination. It is also not very available to animals	Cm-242 is highly particle reactive in the aquatic environment and therefore tends to be accumulated in the bottom sediments.	Cm-242 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Cm-242 deposited in the terrestrial environment will mainly be transferred to soils. It will tend to remain in such soil systems until it decays. In aquatic systems, bottom sediments are the most likely environmental sink and Cm-242 migration will be closely associated with sediment transport	Because of its high particle reactivity, Cm-242 shows low bioavailability to plants. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation (e.g. re-suspended soils and sediments). Although uptake from the gastrointestinal tract is limited (<0.1 %), enhanced concentrations of Cm-242 may occur in the liver and skeleton. Marine and freshwater fish concentrations are about a factor of 50 higher than concentrations in water. Concentrations in molluscs, crustaceans and marine plants can be a factor of 1,000 higher than the surrounding water.

Effects on organisms

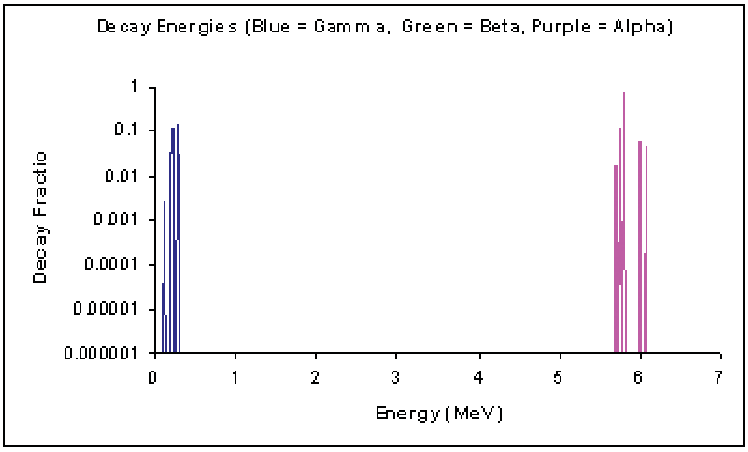
Dose effects/dosimetry	Species-specific considerations
Cm-242 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Cm-242 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	Specific consideration should be given to molluscs, crustaceans and marine plants for which concentration factors can be a factor of 1,000 or more higher than the surrounding water.

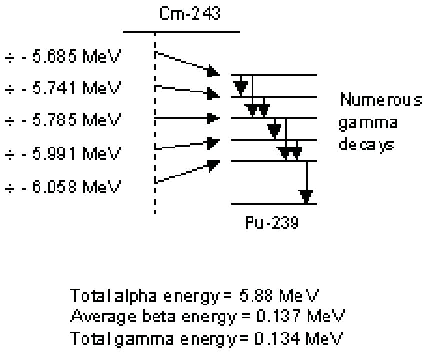
Name	Curium-243	*Symbol*	Cm-243	*Origin*	Breeding
Radioactive half-life	28.5 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	N/A	*Daughter*	Pu-239 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Successive capture of neutrons by plutonium and americium in a nuclear reactor, followed by decay of the products
Uses		• No specific use other than research activities
Modes of release	Land	• Deposition following atmospheric testing of nuclear weapons • As a result of nuclear accidents and releases from nuclear facilities
	Air	• Atmospheric testing of nuclear weapons
	Water	• Leaching from soils to groundwater

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Most curium compounds are based on an oxidation state of +3 for curium. For example, it forms trihalide compounds (e.g. CmF_3), although compounds such as CmO_2 are examples of the +4 oxidation state. Curium and its compounds are capable of the formation and precipitation of colloids and organic complexes.	The two higher actinides, Am and Cm, have very similar chemical, biochemical and biogeochemical characteristics. However, Am has been more extensively studied than Cm, so it is appropriate to regard Am as an analogue for Cm.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cm-243 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination. It is also not very available to animals	Cm-243 is highly particle reactive in the aquatic environment and therefore tends to accumulate in the bottom sediments.	Cm-243 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Cm-243 deposited in the terrestrial environment will mainly be transferred to soils. It will tend to remain in such soil systems until it decays. In aquatic systems, bottom sediments are the most likely environmental sink and Cm-243 migration will be closely associated with sediment transport.	Because of its high particle reactivity, Cm-243 shows low bioavailability to plants. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation (e.g. re-suspended soils and sediments). Although uptake from the gastrointestinal tract is limited (<0.1 %), enhanced concentrations of Cm-243 may occur in the liver and skeleton. Marine and freshwater fish concentrations are about a factor of 50 higher than concentrations in water. Concentrations in molluscs, crustaceans and marine plants can be a factor of 1,000 higher than the surrounding water.

Effects on organisms

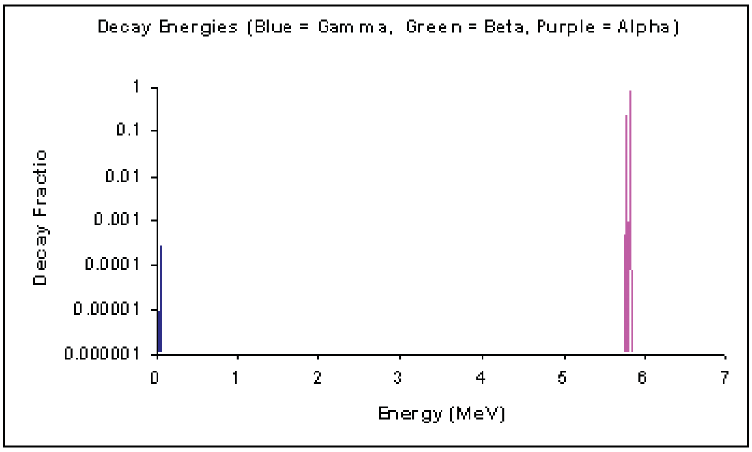
Dose effects/dosimetry	Species-specific considerations
Cm-243 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Cm-243 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	Specific consideration should be given to molluscs, crustaceans and aquatic plants for which concentration factors can be a factor of 1,000 or more higher than the surrounding water.

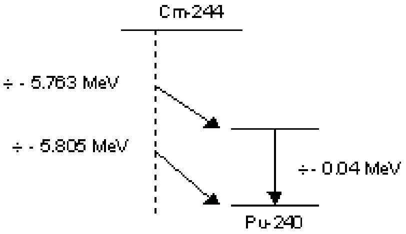
Name	Curium-244	*Symbol*	Cm-244	*Origin*	Breeding
Radioactive half-life	18.1 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Cf-248	*Daughter*	Pu-240 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Successive capture of neutrons by plutonium and americium in a nuclear reactor, followed by decay of the products
Uses		• No specific use other than research activities
Modes of release	Land	• Deposition following atmospheric testing of nuclear weapons • As a result of nuclear accidents and releases from nuclear facilities
	Air	• Atmospheric testing of nuclear weapons
	Water	• Leaching from soils to groundwater

Decay modes





Total alpha energy = 5.89 MeV
Average beta energy = 0.0086 MeV
Total gamma energy = 0.002 MeV

Chemical properties/characteristics

Speciation	Analogue species
Most curium compounds are based on an oxidation state of +3 for curium. For example, it forms trihalide compounds (e.g. CmF_3), although compounds such as CmO_2 are examples of the +4 oxidation state. Curium and its compounds are capable of the formation and precipitation of colloids and organic complexes.	The two higher actinides, Am and Cm, have very similar chemical, biochemical and biogeochemical characteristics. However, Am has been more extensively studied than Cm, so it is appropriate to regard Am as an analogue for Cm.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cm-244 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination. It is also not very available to animals	Cm-244 is highly particle reactive in the aquatic environment and therefore tends to accumulate in the bottom sediments.	Cm-244 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Cm-244 deposited in the terrestrial environment will mainly be transferred to soils. It will tend to remain in such soil systems until it decays. In aquatic systems, bottom sediments are the most likely environmental sink and Cm-244 migration will be closely associated with sediment transport.	Because of its high particle reactivity, Cm-244 shows low bioavailability to plants. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation (e.g. re-suspended soils and sediments). Although uptake from the gastrointestinal tract is limited (<0.1 %), enhanced concentrations of Cm-244 may occur in the liver and skeleton. Marine and freshwater fish concentrations are about a factor of 50 higher than concentrations in water. Concentrations in molluscs, crustaceans and marine plants can be a factor of 1,000 higher than the surrounding water.

Effects on organisms

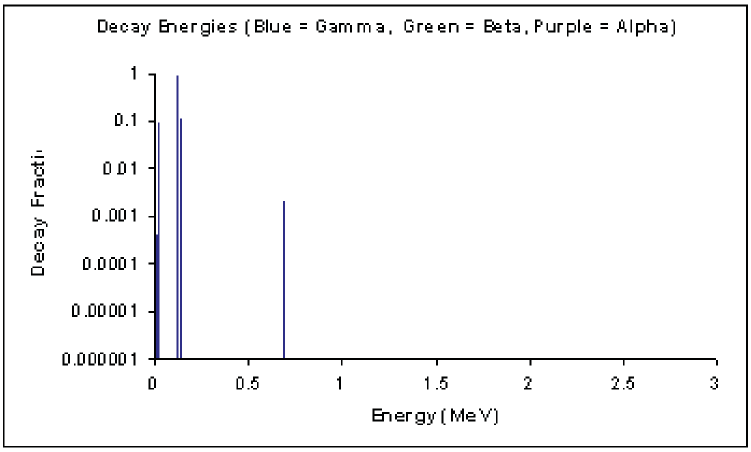
Dose effects/dosimetry	Species-specific considerations
Cm-244 is primarily an alpha emitter. Activity deposited on the outer layers (e.g. skin) of organisms will therefore be of little radiological consequence. Cm-244 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	Specific consideration should be given to molluscs, crustaceans and aquatic plants for which concentration factors can be a factor of 1,000 or more higher than the surrounding water.

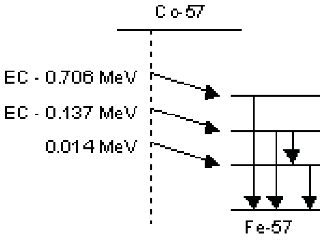
Name	Cobalt-57	*Symbol*	Co-57	*Origin*	Activation
Radioactive half-life	271 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	Cf-248	*Daughter*	Fe-57	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of other transition metals present in the structural steels of reactor vessels
Uses		• In medicine for diagnostic purposes
Modes of release	Land	• Treatment and disposal of spent fuel and reactor hardware
	Air	• Treatment and disposal of spent fuel and reactor hardware
	Water	• Treatment and disposal of spent fuel and reactor hardware

Decay modes





Average beta energy = 0.0186 MeV
Total gamma energy = 0.125 MeV

Chemical properties/characteristics

Speciation	Analogue species
Cobalt is a transition metal element that shows two common oxidation states (+2 and +3). In the +2 state, it forms a wide range of ionic compounds including the oxide, hydroxide and halides. In the +3 oxidation state, it forms a wide range of complexes.	Cobalt is an essential element for animals because of its central role in vitamin B12. Therefore, whereas analogies with other transition metals may be made for plants, this is not thought to be appropriate for animals.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Co-57 is highly particle reactive and tends to be absorbed to the surface of clay minerals through iron and manganese oxides. It can be mobile in organic or acid soils, but tends to be immobile in alkaline or neutral soils.	Co-57 is highly reactive with aquatic sediments and tends to be migrate from the water column to bottom sediments.	Co-57 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. chloride, might also arise

Exposure routes and pathways

Environmental sink	Intake and uptake routes
As Co-57 has a half-life of only 271 days and is highly particle reactive, it can be expected to be retained in terrestrial soils and sediments, and to decay in situ. In the aquatic environment, Co-57 will either decay in the water column or in bottom sediments close to its point of deposition.	Root uptake by plants is not a significant uptake mechanism for Co-57. Cobalt is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~20 %. Animal intakes will be mainly by ingestion of contaminated plants, with a secondary contribution from soil consumption. Concentrations in aquatic plants, molluscs and crustaceans are about 1,000 higher than the surrounding water. Concentration ratios in freshwater fish relative to water vary from about 10 to 1,000 or more. However, values for marine fish are typically about 1.

Effects on organisms

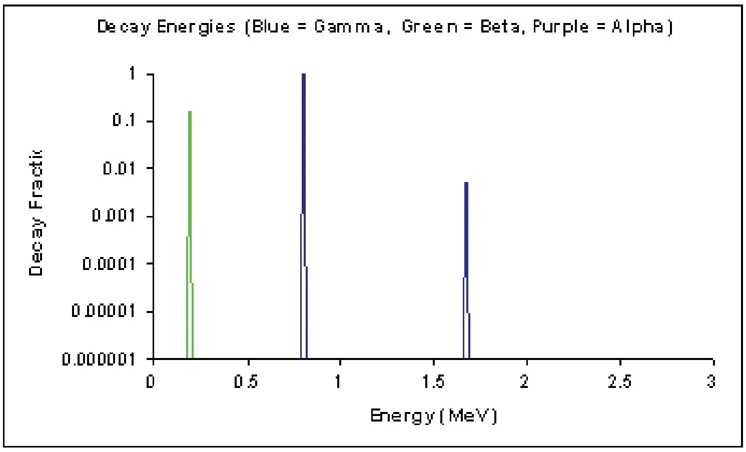
Dose effects/dosimetry	Species-specific considerations
Co-57 emits gamma rays following decay by electron capture. As Co-57 is relatively uniformly distributed in plant and animal tissues, gamma doses to all organs and tissues will be similar.	The high concentration ratios exhibited by many aquatic organisms may mean that these are of particular interest.

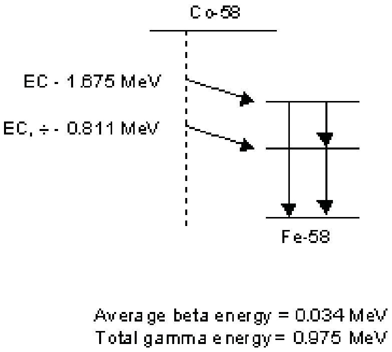
Name	Cobalt-58	*Symbol*	Co-58	*Origin*	Activation
Radioactive half-life	71 days	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Fe-58	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of other transition metals present in the structural steels of reactor vessels
Uses		• In medicine for diagnostic purposes
Modes of release	Land	• Treatment and disposal of spent fuel and reactor hardware
	Air	• Treatment and disposal of spent fuel and reactor hardware
	Water	• Treatment and disposal of spent fuel and reactor hardware

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Cobalt is a transition metal element that shows two common oxidation states (+2 and +3). In the +2 state, it forms a wide range of ionic compounds including the oxide, hydroxide and halides. In the +3 oxidation state, it forms a wide range of complexes.	Cobalt is an essential element for animals because of its central role in vitamin B12. Therefore, whereas analogies with other transition metals may be made for plants, this is not thought to be appropriate for animals.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Co-58 is highly particle reactive and tends to be absorbed to the surface of clay minerals through iron and manganese oxides. It can be mobile in organic or acid soils, but tends to be immobile in alkaline or neutral soils.	Co-58 is highly reactive with aquatic sediments and tends to be migrate from the water column to bottom sediments.	Co-58 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. chloride, might also arise

Exposure routes and pathways

Environmental sink	Intake and uptake routes
As Co-58 has a half-life of only 71 days and is highly particle reactive, it can be expected to be retained in terrestrial soils and sediments, and to decay in situ. In the aquatic environment, Co-58 will either decay in the water column or in bottom sediments close to its point of deposition.	Root uptake by plants is not a significant uptake mechanism for Co-58. Cobalt is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~20 %. Animal intakes will be mainly by ingestion of contaminated plants, with a secondary contribution from soil consumption. Concentrations in aquatic plants, molluscs and crustaceans are about 1,000 higher than the surrounding water. Concentration ratios in freshwater fish relative to water vary from about 10 to 1,000 or more. However, values for marine fish are typically about 1.

Effects on organisms

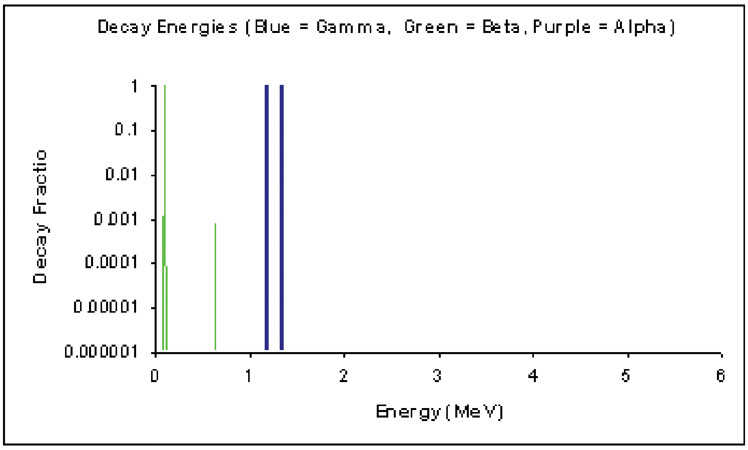
Dose effects/dosimetry	Species-specific considerations
Co-58 is a beta-gamma emitter. As Co-58 is relatively uniformly distributed in plant and animal tissues, gamma doses to all organs and tissues will be similar.	The high concentration ratios exhibited by many aquatic organisms may mean that these are of particular interest.

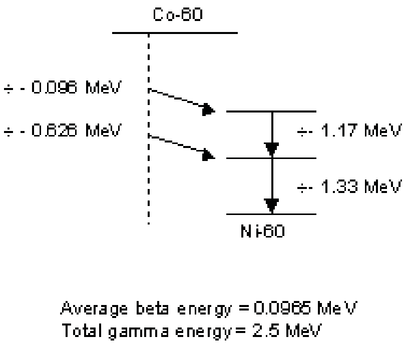
Name	Cobalt-60	*Symbol*	Co-60	*Origin*	Activation
Radioactive half-life	5.27 years	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	Co-60m	*Daughter*	Ni-60	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of stable cobalt-59 present in the structural steels of reactor vessels
Uses		• Detection of flaws in welded joints and castings • In medicine as an irradiation source in the treatment of cancer
Modes of release	Land	• Treatment and disposal of spent fuel and reactor hardware
	Air	• Treatment and disposal of spent fuel and reactor hardware
	Water	• Treatment and disposal of spent fuel and reactor hardware • Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Cobalt is a transition metal element that shows two common oxidation states (+2 and +3). In the +2 state, it forms a wide range of ionic compounds including the oxide, hydroxide and halides. In the +3 oxidation state, it forms a wide range of complexes.	Cobalt is an essential element for animals because of its central role in vitamin B12. Therefore, whereas analogies with other transition metals may be made for plants, this is not thought to be appropriate for animals.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Co-60 is highly particle reactive and tends to be absorbed to the surface of clay minerals through iron and manganese oxides. It can be mobile in organic or acid soils, but tends to be immobile in alkaline or neutral soils.	Co-60 is highly reactive with aquatic sediments and tends to be migrate from the water column to bottom sediments.	Co-60 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. chloride, might also arise

Exposure routes and pathways

Environmental sink	Intake and uptake routes
As Co-60 is highly particle reactive, it can be expected to be retained in terrestrial soils and sediments, and to decay in situ. In the aquatic environment, Co-60 will either decay in the water column or in bottom sediments close to its point of deposition.	Root uptake by plants is not a significant uptake mechanism for Co-60. Cobalt is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~20 %. Animal intakes will be mainly by ingestion of contaminated plants, with a secondary contribution from soil consumption. Concentrations in aquatic plants, molluscs and crustaceans are about 1,000 higher than the surrounding water. Concentration ratios in freshwater fish relative to water vary from about 10 to 1,000 or more. However, values for marine fish are typically about 1.

Effects on organisms

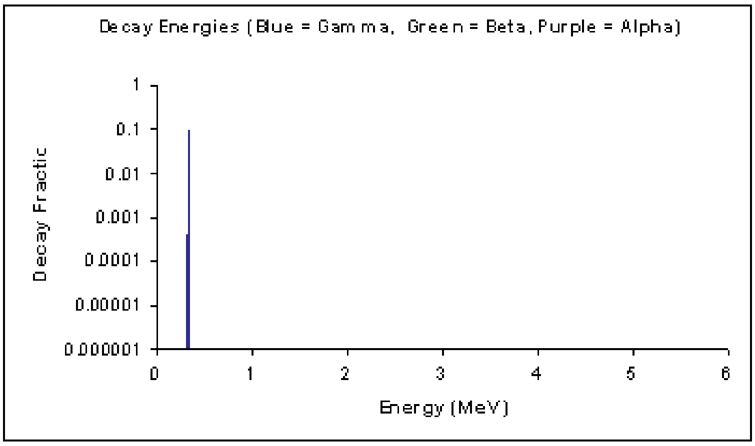
Dose effects/dosimetry	Species-specific considerations
Co-60 is a beta-gamma emitter. As Co-60 is relatively uniformly distributed in plant and animal tissues, gamma doses to all organs and tissues will be similar.	The high concentration ratios exhibited by many aquatic organisms may mean that these are of particular interest.

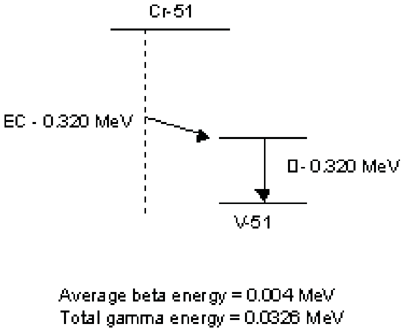
Name	Chromium-51	*Symbol*	Cr-51	*Origin*	Activation
Radioactive half-life	27.7 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	V-51	*Detection*	Laboratory

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• In medicine as a tracer to label red blood cells • To assist in the treatment of bone cancer
Modes of release	Land	• Sewage sludge application to land.
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Chromium is a transition metal that can show all oxidation states from -2 through to +6. The chemistry of chromium and its compounds is therefore very wide and varied. Chromium has a number of oxides, forms compounds with the halogens, and can form organic complexes.	Cr has been extensively studied in its own right, both as an essential trace element and as a chemical carcinogen. Therefore, there is no need to rely on analogues to characterise its behaviour. Cr has some chemical, biochemical and biogeochemical affinities with the other transition metals. However, these affinities are not very close.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Uptake of Cr by plants from soils is limited. Taking into account the short half-life of Cr-51, external deposition on plants is of greatest interest. The availability of Cr to animals is low for trivalent forms but moderate for hexavalent forms.	The degree of interaction of Cr with sediments depends on chemical form. Trivalent Cr is highly sorbed, whereas hexavalent Cr is less strongly sorbed and a substantial fraction can remain in solution.	If Cr-51 was released to atmosphere, it would probably be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The short half-life of Cr-51 means that it will often decay close to its point of deposition in terrestrial environments. In aquatic environments, trivalent Cr-51 is likely to decay in bottom sediments. However, hexavalent Cr-51 may be widely dispersed and mainly decay in the water column.	Uptake of Cr by plants from soils is limited. Taking into account the short half-life of Cr-51, external deposition on plants is of greatest interest. The availability of Cr to animals is low for trivalent forms but moderate for hexavalent forms and Cr incorporated into foodstuffs. Cr-51 exhibits variable, but often high concentration ratios relative to water in aquatic organisms (typically from a few hundred to a few thousand). Cr-51 is likely to be widely distributed throughout the tissues of both terrestrial and aquatic organisms.

Effects on organisms

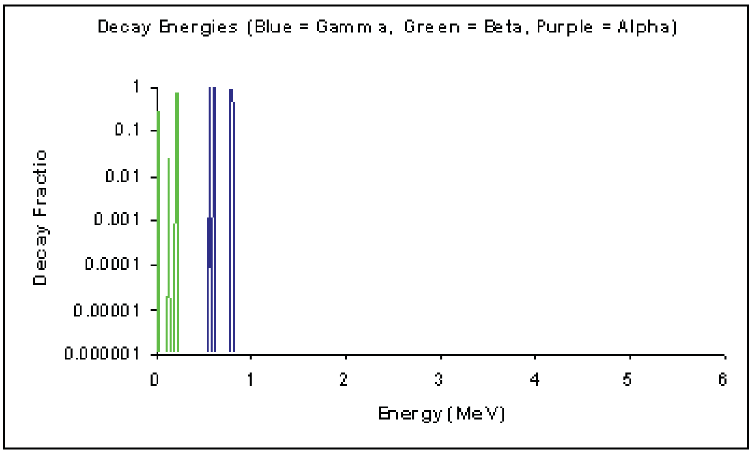
Dose effects/dosimetry	Species-specific considerations
Cr-51 emits a gamma ray of moderate energy in about 10 % of its transformations. As Cr-51 is uniformly distributed through all organs and tissues, the overall dose will be uniformly distributed through the body.	The conservative behaviour of hexavalent Cr-51 in aquatic systems and the high concentration ratios relative to water for Cr-51 of many aquatic organisms make these species of particular interest.

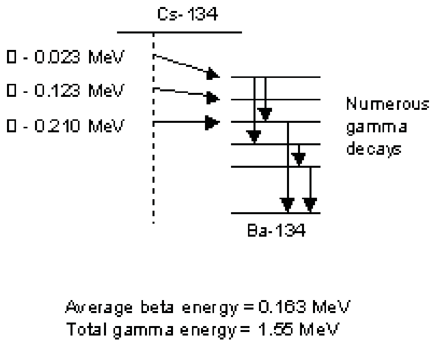
Name	Caesium-134	*Symbol*	Cs-134	*Origin*	Fission
Radioactive half-life	2.06 years	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Ba-134	*Detection*	In situ

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• Uses for scientific research
Modes of release	Land	• Deposition following weapons tests or a nuclear accident
	Air	• Discharge to air following weapons tests or a nuclear accident
	Water	• Discharge to the sea from operating nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Caesium is an alkali metal whose chemical behaviour is determined by the properties of the Cs^+ ion. Most of the compounds of caesium are ionic in nature, although more complex species can be formed. Caesium reacts extremely vigorously with water, oxygen and halogens.	Cr has been extensively studied in its own right, both as an essential trace element and as a chemical carcinogen. Therefore, there is no need to rely on analogues to characterise its behaviour. Cr has some chemical, biochemical and biogeochemical affinities with the other transition metals. However, these affinities are not very close.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cs-134 binds strongly to the clay fraction in soils and sediments. However, it can also be relatively highly available for plant uptake, particularly in organic and K-deficient soils. Cs-134 is transferred from plant surfaces to soils in around 5-30 days.	Cs-134 is moderately particle reactive in marine environments, so dispersion in waters and loss to bottom sediments are both possible. In freshwaters, Cs-134 can be more highly particle reactive and subject to local deposition.	Cs is a highly volatile element. Thus, Cs-134 is likely to be of importance in atmospheric releases from nuclear accidents. It would be released and dispersed as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The high particle reactivity of Cs-134 means that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, Cs-134 can be widely dispersed and may decay either in the water column or in deposited sediments.	Cs-134 can be relatively highly available for plant uptake, particularly in organic and K-deficient soils. Cs-134 is highly bioavailable to animals and is almost completely absorbed from the gastrointestinal tract. It distributes reasonably uniformly through most organs and tissues of the body, but concentrates to some degree in muscle. Concentration ratios relative to water are about 100 for marine fish, 30-50 for marine invertebrates and plants, but about 1,000 for freshwater fish. Muscle is the primary site of deposition in freshwater fish.

Effects on organisms

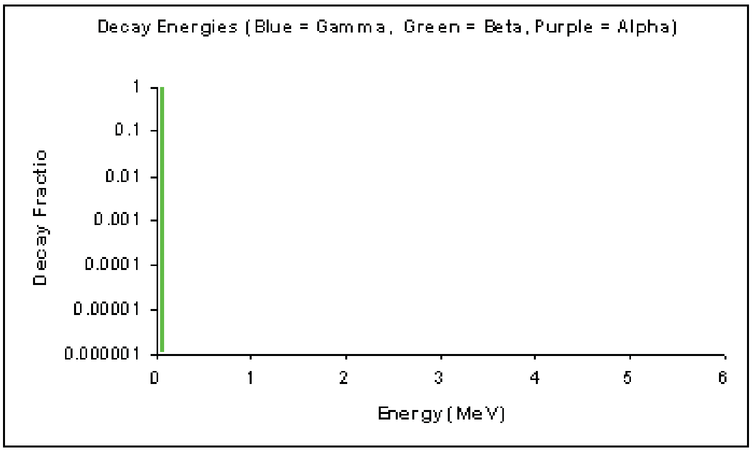
Dose effects/dosimetry	Species-specific considerations
The main emissions from Cs-134 are moderately energetic gamma rays. Therefore, external irradiation, e.g. from soils and sediments, can be important. The relatively uniform distribution of Cs-134 in biota and the penetrating power of the emitted gamma rays mean that individual organ and tissue doses are generally of comparable magnitude to the average whole-body dose.	The high concentration ratios for freshwater fish make the exposure of freshwater fish appropriate for specific consideration. Plant uptake in K-deficient areas or areas with organic soils subject to wet deposition is also of potential importance. Uptake in animals grazing such areas also needs to be considered.

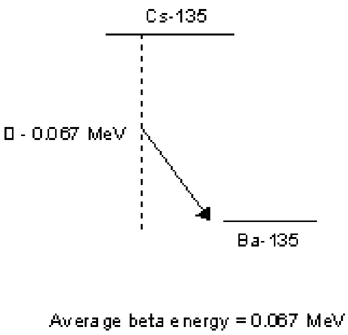
Name	Caesium-135	*Symbol*	Cs-135	*Origin*	Fission
Radioactive half-life	2.3 x 10^6 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Ba-135	*Detection*	Laboratory

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• No specific uses, except for scientific research
Modes of release	Land	• Deposition following weapons tests or a nuclear accident
	Air	• Discharge to air following weapons tests or a nuclear accident
	Water	• Discharge to the sea from operating nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Caesium is an alkali metal whose chemical behaviour is determined by the properties of the Cs^+ ion. Most of the compounds of caesium are ionic in nature, although more complex species can be formed. Caesium reacts extremely vigorously with water, oxygen and halogens.	Cs exhibits many chemical, biochemical and biogeochemical similarities to K. Cs:K ratios have often been used to characterise the environmental behaviour of Cs.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cs-135 binds strongly to the clay fraction in soils and sediments. However, it can also be relatively highly available for plant uptake, particularly in organic and K-deficient soils. Cs-135 is translocated from plant surfaces to soils in around 5-30 days	Cs-135 is moderately particle reactive in marine environments, so dispersion in waters competes effectively with loss to bottom sediments. In freshwaters, Cs-135 can be more highly particle reactive and subject to local deposition.	Cs is a highly volatile element. Thus, Cs-135 is likely to be of importance in atmospheric releases from nuclear accidents. It would be released and dispersed as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The high particle reactivity of Cs-135 means that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, Cs-135 can be widely dispersed and may decay either in the water column or in deposited sediments.	Cs-135 can be relatively highly available for plant uptake, particularly in organic and K-deficient soils. Cs-135 is highly bioavailable to animals and is almost completely absorbed from the gastrointestinal tract. It distributes reasonably uniformly throughout all organs and tissues of the body, but concentrates to some degree in muscle. Concentration ratios relative to water are about 100 for marine fish, 30-50 for marine invertebrates and plants, but about 1,000 for freshwater fish. Muscle is the primary site of deposition in freshwater fish.

Effects on organisms

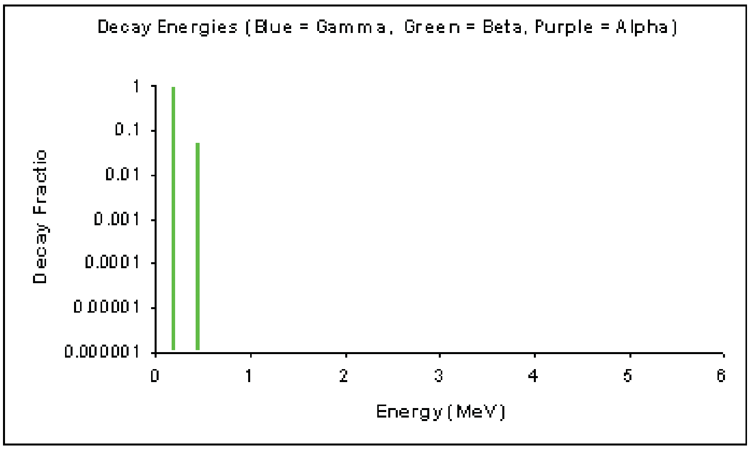
Dose effects/dosimetry	Species-specific considerations
Cs-135 is a soft beta emitter. Therefore, external exposure is of no importance. Because Cs-135 is relatively uniformly distributed in tissues, doses to individual organs and tissues are of comparable magnitude to average whole-body doses.	The high concentration ratios for freshwater fish make the exposure of freshwater fish appropriate for specific consideration. Plant uptake in K-deficient areas or areas with organic soils subject to wet deposition is also of potential importance. Uptake in animals grazing such areas also needs to be considered.

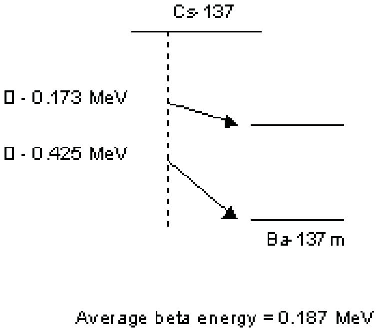
Name	Caesium-137	*Symbol*	Cs-137	*Origin*	Fission
Radioactive half-life	30 years	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Ba-137m [R]	*Detection*	In situ

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• As a radiation source in the treatment of cancer (brachytherapy) • For detecting cracks and imperfections in metal structures
Modes of release	Land	• Deposition following weapons tests or a nuclear accident • Disposal of medical sources
	Air	• Discharge to air following weapons tests or a nuclear accident
	Water	• Discharge to the sea from operating nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Caesium is an alkali metal whose chemical behaviour is determined by the properties of the Cs^+ ion. Most of the compounds of caesium are ionic in nature, although more complex species can be formed. Caesium reacts extremely vigorously with water, oxygen and halogens.	Cs exhibits many chemical, biochemical and biogeochemical similarities to K. Cs:K ratios have often been used to characterise the environmental behaviour of Cs.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Cs-137 binds strongly to the clay fraction in soils and sediments. However, it can also be relatively highly available for plant uptake, particularly in organic and K-deficient soils. Cs-137 is translocated from plant surfaces to soils in around 5-30 days	Cs-137 is moderately particle reactive in marine environments, so dispersion in waters competes effectively with loss to bottom sediments. In freshwaters, Cs-137 can be more highly particle reactive and subject to local deposition.	Cs is a highly volatile element. Thus, Cs-137 is likely to be of importance in atmospheric releases from nuclear accidents. It would be released and dispersed as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The high particle reactivity of Cs-137 means that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, Cs-137 can be widely dispersed and may decay either in the water column or in deposited sediments.	Cs-137 can be relatively highly available for plant uptake, particularly in organic and K-deficient soils. Cs-137 is highly bioavailable to animals and is almost completely absorbed from the gastrointestinal tract. It distributes reasonably uniformly throughout all organs and tissues of the body, but concentrates to some degree in muscle. Concentration ratios relative to water are about 100 for marine fish, 30-50 for marine invertebrates and plants, but about 1,000 for freshwater fish. Muscle is the primary site of deposition in freshwater fish.

Effects on organisms

Dose effects/dosimetry	Species-specific considerations
The main emissions from Cs-137 and its very short-lived daughter Ba-137m are beta particles and moderately energetic gamma rays. Therefore, external irradiation (e.g. from soils and sediments) can be important. The relatively uniform distribution of Cs-137 in biota means that individual organ and tissue doses are of comparable magnitude to the average whole-body dose.	The high concentration ratios for freshwater fish make the exposure of freshwater fish appropriate for specific consideration. Plant uptake in K-deficient areas or areas with organic soils subject to wet deposition is also of potential importance. Uptake in animals grazing such areas also needs to be considered.

Name	Depleted uranium	*Symbol*	Depleted uranium	*Origin*	Primordial
Radioactive half-life	4.46 x 10^9 years	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	N/A	*Daughter*	U-234 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• By removal of much but not all uranium-235 from uranium ore through the production of uranium hexafluoride, followed by conversion to other chemical forms, e.g. uranium oxide or uranium metal
Uses		• Use as tank armour and armour piercing projectiles • As a material for radiation shielding
Modes of release	Land	• From military testing or application on the battlefield
	Air	• As an aerosol from military testing or application on the battlefield
	Water	• Not generally released to water

Decay modes

Chemical properties/characteristics

Speciation	Analogue species
Uranium can exist in any one of four oxidation states, with the +4 state being favoured in reducing conditions and the +6 state in oxidising conditions. Uranium forms a wide range of halide and oxide compounds. The hydroxide and carbonate are also known, and uranium can participate in the formation of organic complexes. U is a ‘chemical’ problem rather than a ‘radiotoxicity’ problem.	Depleted U is uranium in which the proportion of U-235 is reduced, typically by a factor of 3 or 4. However, its chemical characteristics are unchanged. For this reason, there is no requirement to identify analogue elements (see the entry for U-238).

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Uranium is not strongly adsorbed to soils. However, its behaviour is redox sensitive and it can accumulate in reducing horizons. In general, it is strongly excluded from plants.	Uranium behaves conservatively in aqueous environments. It is not strongly accumulated by aquatic organisms.	U-238 released to atmosphere would be expected to disperse as an aerosol. Oxide forms would dominate if the release was due to battlefield activities.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Depleted U entering the environment due to human activities may be mobile, migrating through the aqueous environment.	In general, uranium is strongly excluded from plants, although grain can show greater accumulation of uranium than other plant types. Intakes from plant material and in soil are likely to be of comparable importance for animals. Uranium is not very bioavailable to animals -- the fractional gastrointestinal absorption is typically 1-%2 %. Mineral bone is the principal site of accumulation. Concentration ratios relative to water are about 10 for freshwater and marine fish and crustaceans. Concentration ratios for molluscs can be a little higher (~30) and values ~100 are typical of marine plants.

Effects on organisms

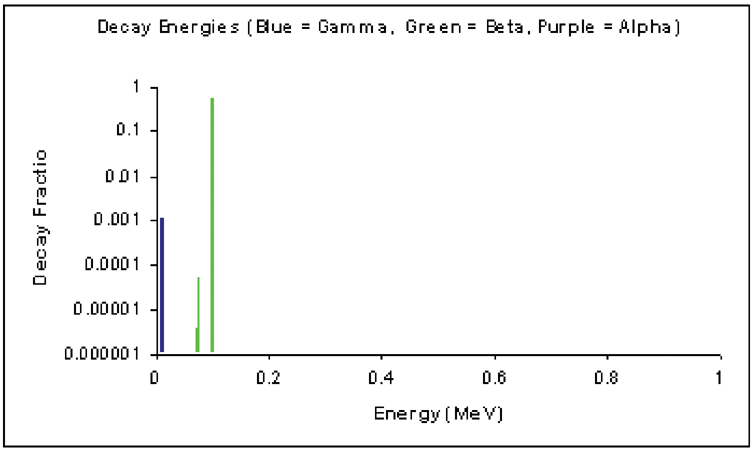
Dose effects/dosimetry	Species-specific considerations
Depleted uranium is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, depleted uranium is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

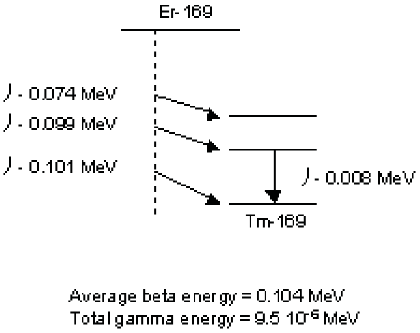
Name	Erbium-169	Symbol	Er-169	Origin	Activation
Radioactive half-life	9.4 days	Principal decay mode	Beta	Grouping	Artificial
Parent	N/A	Daughter	Tm-169	Detection	Laboratory

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• No significant uses outside research activities
Modes of release	Land	• During treatment and disposal of spent fuel
	Air	• During treatment and disposal of spent fuel
	Water	• During treatment and disposal of spent fuel

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Erbium is a rare-earth element that shows an oxidation state of +3. As such, erbium forms compounds with hydrogen, oxygen and the halides. It also forms stable complexes.	The rare earth elements (Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) exhibit similar chemical, biochemical and biogeochemical characteristics. However, these characteristics change systematically in the group with increasing atomic number. Cerium is one of the best-studied members of the group. Analogies with other members and with higher actinides, such as Am, can be useful.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Er-169 is highly particle reactive, and hence would remain bound to soil particles and on the surfaces of plants. Transfers from plant to soil and bulk movement of soils would be the main transport mechanisms.	Er-169 is highly particle reactive. It is likely to bind to suspended sediments close to its point of discharge. It may be rapidly lost by deposition from the water column to sediments.	If Er-169 was released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The short half-life and high particle reactivity of Er-169 mean that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, bottom sediments close to the source of release may form an important sink.	Er-169 is not very bioavailable to animals. The fractional gastrointestinal absorption is typically <0.001. Any Er-169 that is absorbed is mainly deposited in the liver and skeleton. Intake by terrestrial animals is likely to be mainly the ingestion of Er-169 present on the exterior surfaces of plants or deposited on soil. Very little uptake from the gastrointestinal tract is anticipated, except perhaps in pre-weaned animals. In the aquatic environment, uptake by fish and invertebrates is mainly direct from the water rather than food. Uptake by aquatic plants is likely to be by surface adsorption.

Effects on organisms

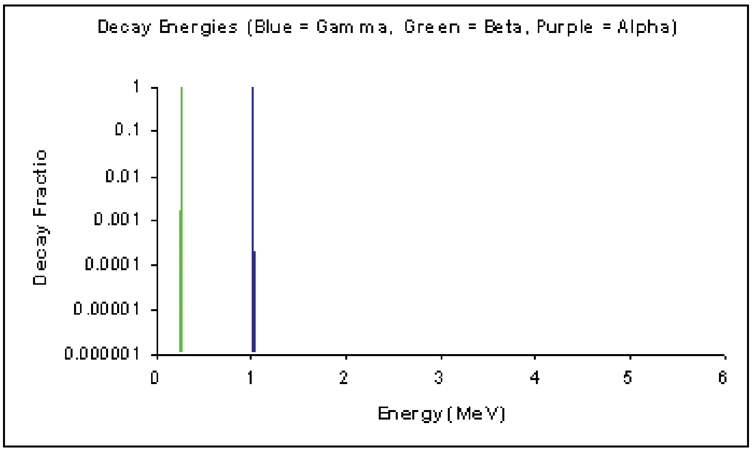
Dose effects/dosimetry	Species-specific considerations
Er-169 is primarily a beta emitter, with negligible emission of gamma rays. This means that only superficial tissues (to a depth of a few millimetres) will be exposed from external irradiation. Internal irradiation will be limited because of the low bioavailability of Er-169.	In mammals and birds, the walls of the gastrointestinal tract are likely to receive substantially higher doses than other organs and tissues.

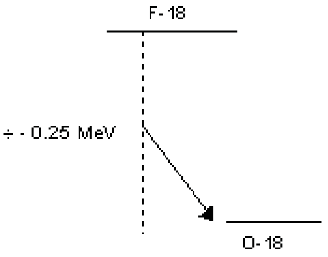
Name	Fluorine-18	Symbol	F-18	Origin	Activation
Radioactive half-life	110 minutes	Principal decay mode	Beta [gamma]	Grouping	Artificial
Parent	N/A	Daughter	O-18	Detection	Laboratory

Production, uses and modes of release

Production		• Irradiation of stable precursors with neutrons in a nuclear reactor or cyclotron
Uses		• In medical diagnosis using positron emission tomography
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Average beta energy = 0.25 MeV
Total gamma energy = 1.02 MeV

Chemical properties/characteristics

Speciation	Analogue species
Fluorine is a halogen element that shows a single oxidation state of -1. It is extremely reactive and forms compounds with most other elements, with the exception of the noble gases.	Although fluorine could be considered analogous to chlorine and iodine, this is of little relevance to the environmental behaviour of F-18 because of its very short radioactive half-life.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Direct discharges of F-18 to the terrestrial environment would not be expected to occur.	Discharges to sewers could occur. However, the F-18 would decay almost completely during its transport through the sewer system.	F-18 could be released to atmosphere at the time of its production. With a half-life of 110 minutes, it could be dispersed downwind over a distance of up to about 30 km.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its very short radioactive half-life, the primary environmental sink for F-18 is radioactive decay.	Fluorine is not highly accumulated by plants from soils. Although some uptake could occur, the very short half-life of F-18 means that external plant contamination from atmospheric deposition or submersion in the plume is likely to be of greatest interest. For animals, inhalation is likely to be the main route. Fluorine is rapidly absorbed from both the respiratory and gastrointestinal tracts, and is then rapidly and efficiently deposited in calcified tissues

Effects on organisms

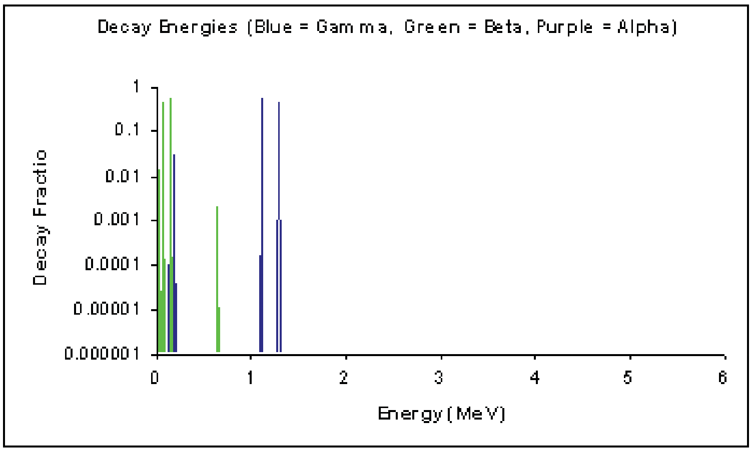
Dose effects/dosimetry	Species-specific considerations
F-18 is a beta-gamma emitter. External gamma irradiation is likely to be of greatest significance, although the very short half-life of F-18 will limit the total dose.	No major species-specific considerations

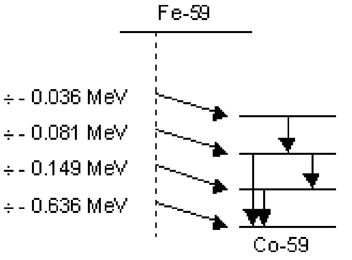
Name	Iron-59	*Symbol*	Fe-59	*Origin*	Activation
Radioactive half-life	44.5 days	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Co-59	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• Investigations of iron metabolism in the spleen
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air
	Water	• Could be released to sewers

Decay modes





Average beta energy = 0.117 MeV
Total gamma energy = 1.19 MeV

Chemical properties/characteristics

Speciation	Analogue species
Iron is a transition metal that shows a number of oxidation states, of which +2 and +3 are the most important. Of these, the +2 state is the most stable. Iron forms a number of simple (e.g. sulphate, nitrate) and organometallic compounds.	Because Fe is an essential element for a wide variety of biota, it is most appropriately considered in its own right rather than as an analogue of other transition metals.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Because of the short radioactive half-life of Fe-59, deposition on plants will be of much greater importance than uptake from soil. As Fe is highly particle reactive, the bulk movement of soils will be the main transport mechanism	Because Fe-59 is highly particle reactive, it will adsorb strongly to suspended sediments and migrate to bottom sediments by deposition of particles.	If Fe-59 is released to the atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In the terrestrial environment, Fe-59 will decay mainly close to its site of deposition. In the aquatic environment, Fe-59 will either decay in the water column or in deposited sediment.	In the terrestrial environment, Fe-59 will mainly be present on the external surfaces of plants. Contamination on plants may be ingested by animals. Bioavailability of Fe-59 to animals depends both on chemical form and iron concentration. Fractional gastrointestinal absorption is typically ~10 %. In mammals and birds, uptake from the gastrointestinal tract will result in accumulation in the liver, spleen and other soft tissues. Concentration ratios in freshwater and marine organisms relative to water range from a few hundred to more than 10,000 and there are no strong distinctions between types.

Effects on organisms

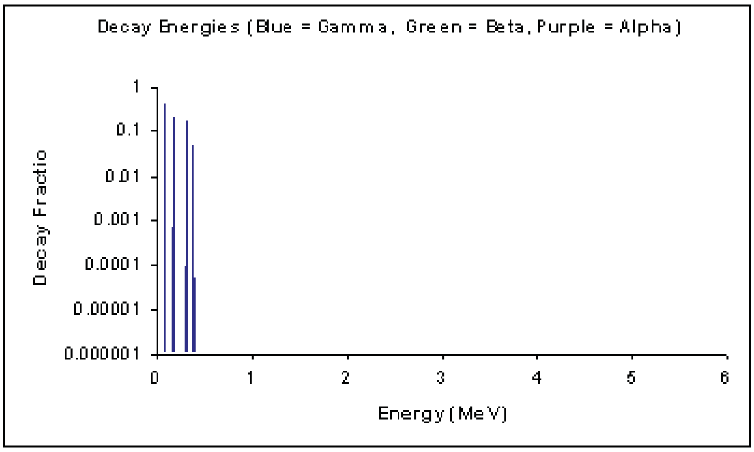
Dose effects/dosimetry	Species-specific considerations
Fe-59 emits two gamma rays with high yield and energies above 1 MeV. Therefore, external irradiation from a dispersing plume and from ground deposits can be of importance. Uptake in plants is of little significance for dosimetric purposes, but uptake and retention in larger animals could result in a substantial contribution from internal dose.	Special consideration should be given to freshwater fish due to the high concentration ratios that can arise.

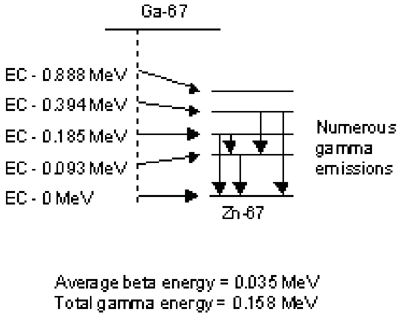
Name	Gallium-67	*Symbol*	Ga-67	*Origin*	Activation
Radioactive half-life	3.3 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Zn-67	*Detection*	In situ

Production, uses and modes of release

Production		• Generally produced in a cyclotron
Uses		• In medical diagnostics for imaging tumours and lesions
Modes of release	Land	• Sewage sludge application to land, but would probably decay substantially before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Gallium is a Group III element whose predominant oxidation state is +3. Some compounds with an oxidation state of +1 are known, but these are relatively unstable. Gallium forms compounds with the halides, oxygen and sulphur.	The are no obvious analogues for the environmental behaviour of Ga.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Because of its short radioactive half-life, deposition on plants will be of much greater importance than uptake from soil. Ga-67 would be expected to be present as external contamination of plant surfaces.	Little is known of the dispersion of Ga-67 in aquatic environments.	If Ga-67 is released to atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The short half-life of Ga-67 means that it will decay in terrestrial environments close to its point of deposition. It is unlikely to disperse over long distances in aquatic environments before it decays.	Little biotic transfer of Ga-67 is likely. Ga-67 would be expected to be present as external contamination of plant surfaces and not subject to significant gastrointestinal absorption.

Effects on organisms

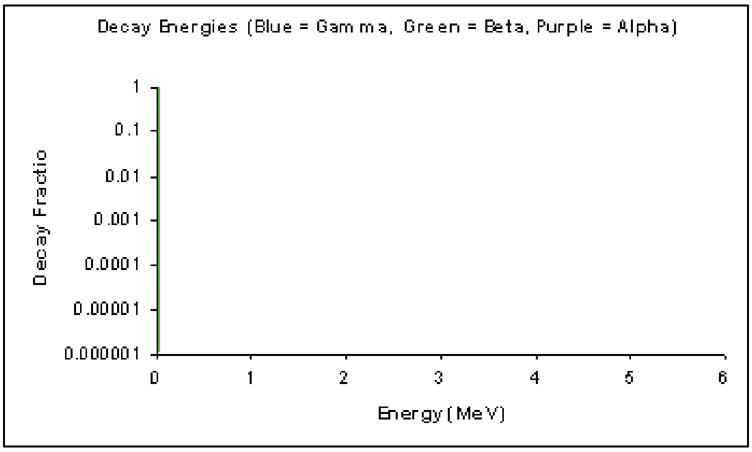
Dose effects/dosimetry	Species-specific considerations
Ga-67 mainly emits moderately low energy gamma emissions. However, in view of its low bioavailability, external irradiation may be the main route of exposure of biota.	As biotic availability is thought to be low, there are no major species-specific considerations.

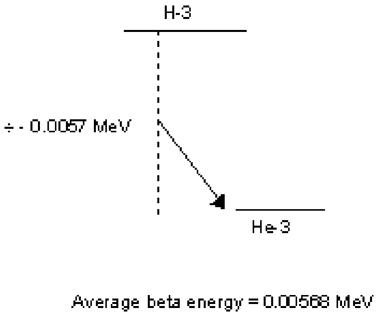
Name	Tritium	*Symbol*	H-3	*Origin*	Cosmogenic
Radioactive half-life	12.4 years	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	N/A	*Daughter*	He-3	*Detection*	Laboratory

Production, uses and modes of release

Production		• Through cosmic ray interactions in the upper atmosphere • Neutron irradiation of lithium-6 • As a fission product in nuclear reactors
Uses		• As a tracer in biological and environmental studies • As a component in nuclear weapons • As an agent in luminous paints for various applications
Modes of release	Land	• Deposition from fallout from weapons tests or a nuclear accident
	Air	• Fallout from weapons tests or a nuclear accident
	Water	• Natural atmospheric processes • Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Hydrogen occurs freely in nature as H_2, but combines with most elements to form hydrides. Hydrogen is a major component of most organic molecules and thus tritium can exchange with hydrogen-1 and become bound to such molecules. In the environment, water is by far the most important hydrogen-containing compound.	There is no appropriate analogue for H, nor is one needed, as the environmental behaviour of various forms of H has been extensively studied.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
H-3 disperses in the terrestrial environment in flows of surface and ground waters. Some conversion from tritiated water to OBT (organically bound tritium) occurs in plants.	Cosmogenically produced H-3 mixes with surface water bodies throughout the world. In general, H-3 is highly conservative and is rapidly dispersed. Aquatic organisms can accumulate H-3 either as tritiated water, or following conversion in the environmentas OBT.	H-3 can be dispersed in the atmosphere as water vapour, elemental hydrogen or as a component of other gases, such as methane. It is ubiquitously present in water vapour from cosmogenic production.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Ocean waters are the main sink for H-3. These waters exchange H-3 with the atmosphere, so the environmental sink is best considered as the two together.	H-3 is readily taken up by plants. Some conversion from tritiated water to OBT occurs in plants. In animals, uptake and retention is mainly of tritiated water, for example from plants and drinking water. Aquatic organisms take up H-3 by exchange from the surrounding water and through the food chain.

Effects on organisms

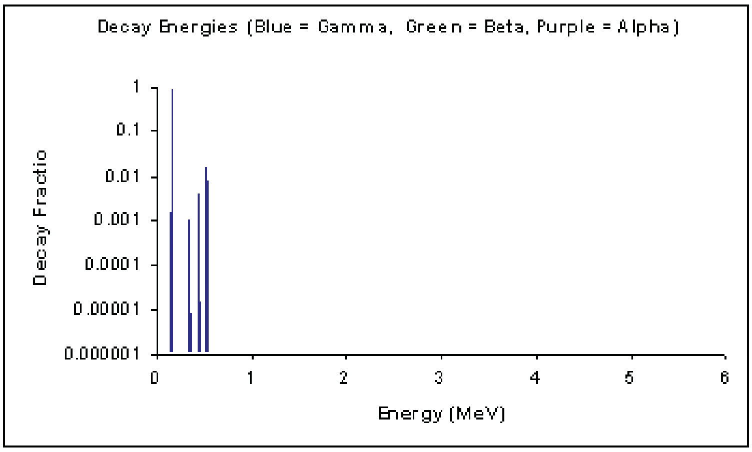
Dose effects/dosimetry	Species-specific considerations
H-3 is a soft beta emitter and is generally relatively uniformly distributed throughout all body tissues. Thus, doses to individual tissues are generally of similar magnitude to average whole-body doses.	As H-3 is ubiquitously present in water in nearly all biota, there are no major species-specific considerations.

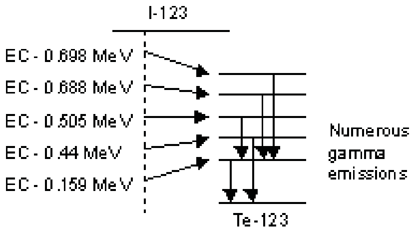
Name	Iodine-123	*Symbol*	I-123	*Origin*	Fission
Radioactive half-life	13.2 hours	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Te-123 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• Biochemical analyses in the biological and life sciences
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air, but some releases of volatile iodine compounds may occur from sewage sludge
	Water	• Hospital releases to sewers

Decay modes





Average beta energy = 0.028 MeV
Total gamma energy = 0.171 MeV

Chemical properties/characteristics

Speciation	Analogue species
Iodine is a halogen element that exhibits a number of stable oxidation states. Two of the most important of these are the -1 (iodide) and +5 (iodate) compounds. Iodine can also take part in the formation of organic complexes.	There are chemical similarities between F, Cl, Br and I. However, I is an essential trace element that has specific biochemical roles and it has been extensively studied. Therefore, there is no need to rely on analogues to characterise its environmental behaviour.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
I-123 has a very short half-life. Following deposition, it will mainly be present on the external surfaces of plants. As iodine is not particularly particle reactive, I-123 will migrate in surface or groundwaters through the terrestrial environment.	Because iodine is not particularly particle reactive, it will disperse freely in aquatic systems, although some binding to sediments can be expected.	Iodine released to the atmosphere may disperse as a vapour of the element, as an aerosol or as methyl iodide. Elemental iodine and aerosol particles are efficiently deposited to surfaces; this is not the case for methyl iodide.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The very short half-life of I-123 means that it mainly decays as it disperses through the environment. Iodine only exhibits a limited degree of sorption to mineral solids, but it can have a high affinity for organic matter.	I-123 will mainly be present on the external surfaces of plants, with some translocation to inner plant parts. It is highly bioavailable, being completely absorbed from the gastrointestinal tract of mammals and birds. Although very short-lived, its half-life is long enough for it to be translocated to the thyroid. Iodine is only concentrated to a limited degree in most freshwater and marine organisms, with the exception of marine plants (e.g. some algae and seaweeds).

Effects on organisms

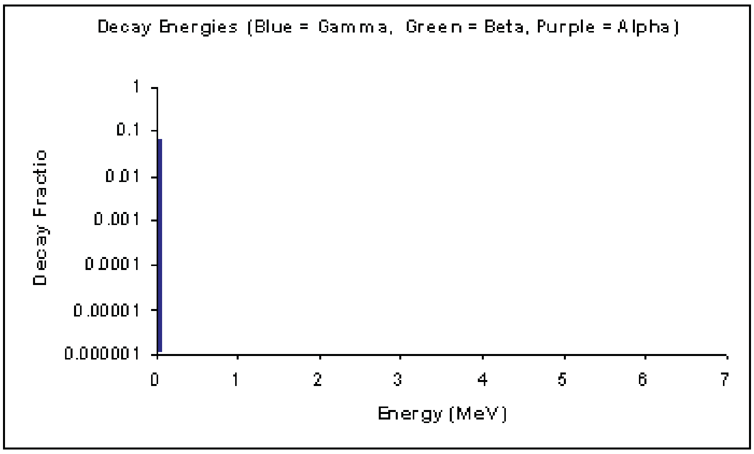
Dose effects/dosimetry	Species-specific considerations
I-123 emits mainly relatively low energy gamma rays. Because of its high degree of concentration in the thyroids of mammals and birds, radiation dose to the thyroid is of primary interest, although gamma doses to other organs may be significant. At lower doses, thyroid cancer would be the effect of particular interest but, at very high doses, hypothyroidism might occur.	No major species-specific considerations, although it should be noted that uptake to the thyroid is strongly determined by the level of stable iodine present in the diet.

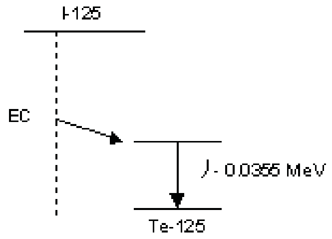
Name	Iodine-125	*Symbol*	I-125	*Origin*	Fission
Radioactive half-life	59.4 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Te-125	*Detection*	Laboratory

Production, uses and modes of release

Production		• Irradiation of stable nuclides in a reactor or cyclotron
Uses		• Treatment of thyroid cancer • Biochemical analyses in medicine and the life sciences
Modes of release	Land	• Release from hospitals or research facilities
	Air	• Release from hospitals or research facilities
	Water	• Could be released to sewers

Decay modes





Average beta energy = 0.019 MeV
Total gamma energy = 0.042 MeV

Chemical properties/characteristics

Speciation	Analogue species
Iodine is a halogen element that exhibits a number of stable oxidation states. Two of the most important of these are the -1 (iodide) and +5 (iodate) compounds. Iodine can also take part in the formation of organic complexes.	There are chemical similarities between F, Cl, Br and I. However, I is an essential trace element that has specific biochemical roles and it has been extensively studied. Therefore, there is no need to rely on analogues to characterise its environmental behaviour.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Following deposition, I-125 will mainly be present on the external surfaces of plants. As iodine is not particularly particle reactive, I-125 present in soils will tend to migrate in surface or groundwaters through the terrestrial environment.	Because iodine is not particularly particle reactive, it will disperse freely in aquatic systems, although some binding to sediments can be expected.	Iodine released to the atmosphere may disperse as a vapour of the element, as an aerosol or as methyl iodide. Whereas elemental iodine and aerosol particles are efficiently deposited to surfaces, this is not the case for methyl iodide.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
I-125 mainly decays as it disperses through the environment. Iodine only exhibits a limited degree of sorption to mineral solids, but it can have a high affinity for organic matter.	I-125 will mainly be present on the external surfaces of plants, with some translocation to inner plant parts. It is highly bioavailable, being completely absorbed from the gastrointestinal tract of mammals and birds. I-125 entering the systemic circulation of mammals and birds is translocated to the thyroid. Iodine is only concentrated to a limited degree in most freshwater and marine organisms, with the exception of marine plants (e.g. some algae and seaweeds).

Effects on organisms

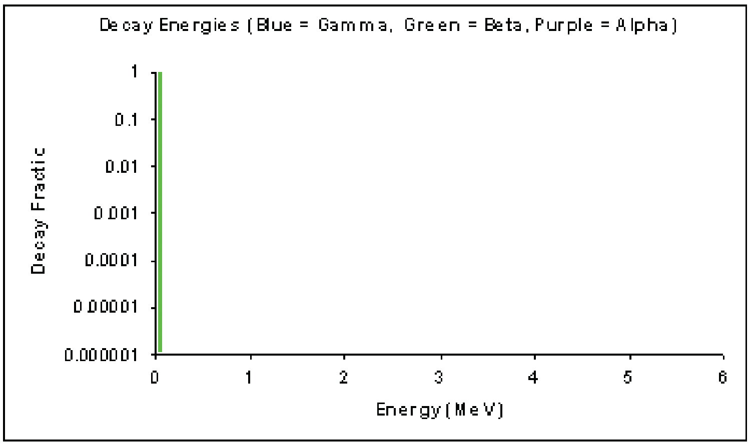
Dose effects/dosimetry	Species-specific considerations
I-125 emits low energy photons and Auger electrons (see Glossary). Because of its high degree of concentration in the thyroids of mammals and birds, radiation dose to the thyroid is of primary interest. At lower doses, thyroid cancer would be the effect of particular interest but, at very high doses, hypothyroidism might occur.	No major species-specific considerations, although it should be noted that uptake to the thyroid is strongly determined by the level of stable iodine present in the diet.

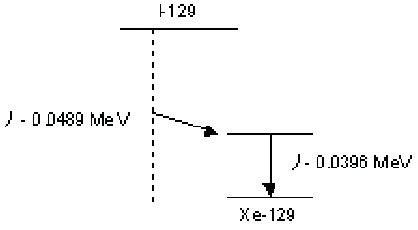
Name	Iodine-129	*Symbol*	I-129	*Origin*	Fission
Radioactive half-life	1.57×10^7 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Xe-129	*Detection*	Laboratory

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• No significant uses outside research activities
Modes of release	Land	• Deposition following historic atmospheric nuclear weapons tests • Release from nuclear facilities
	Air	• Releases during historic nuclear weapons test • Release from nuclear facilities
	Water	• Liquid discharges from nuclear facilities

Decay modes





Average beta energy = 0.0638 MeV
Total gamma energy = 0.0246 MeV

Chemical properties/characteristics

Speciation	Analogue species
Iodine is a halogen element that exhibits a number of stable oxidation states. Two of the most important of these are the -1 (iodide) and +5 (iodate) compounds. Iodine can also take part in the formation of organic complexes.	There are chemical similarities between F, Cl, Br and I. However, I is an essential trace element that has specific biochemical roles and it has been extensively studied. Therefore, there is no need to rely on analogues to characterise its environmental behaviour.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Following deposition, I-129 will mainly be present on the external surfaces of plants. As iodine is not particularly particle reactive, I-129 present in soils will tend to migrate in surface or groundwaters through the terrestrial environment.	Because iodine is not particularly particle reactive, it will disperse freely in aquatic systems, although some binding to sediments can be expected.	Iodine released to the atmosphere may disperse as a vapour of the element, as an aerosol or as methyl iodide. Whereas elemental iodine and aerosol particles are efficiently deposited to surfaces, this is not the case for methyl iodide.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
I-129 becomes widely dispersed in the worldís oceans. In the very long term, there may be some translocation of this I-129 to organic-rich bottom sediments.	I-129 will mainly be present on the external surfaces of plants, with some translocation to inner plant parts. It is highly bioavailable, being completely absorbed from the gastrointestinal tract of mammals and birds, following ingestion of contaminated foodstuffs and drinking water. I-129 entering the systemic circulation of mammals and birds is translocated to the thyroid. Iodine is only concentrated to a limited degree in most freshwater and marine organisms, with the exception of marine plants (e.g. some algae and seaweeds).

Effects on organisms

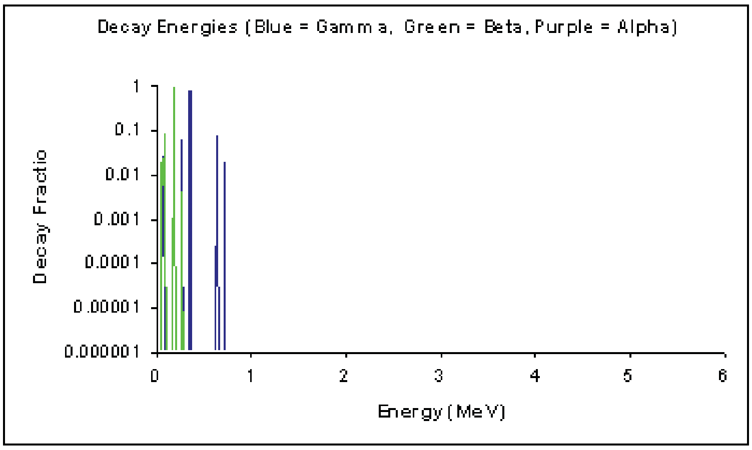
Dose effects/dosimetry	Species-specific considerations
I-129 emits beta particles, low gamma rays and Auger electrons (see Glossary). Because of its high degree of concentration in the thyroids of mammals and birds, radiation dose to the thyroid is of primary interest. Because of its very low specific activity, there is no possibility of delivering high doses to the thyroid, so the potential induction of thyroid cancer is the only effect that could be of interest.	No major species-specific considerations, although it should be noted that uptake to the thyroid is strongly determined by the level of stable iodine present in the diet.

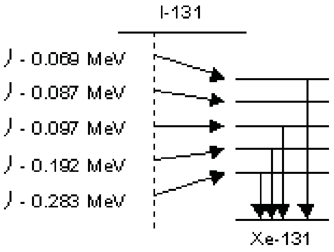
Name	Iodine-131	*Symbol*	I-131	*Origin*	Fission
Radioactive half-life	8.02 days	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Xe-131	*Detection*	In situ

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• Treatment of thyroid and (sometimes) bone cancer • Biochemical analyses in medicine and the life sciences
Modes of release	Land	• Deposition following a nuclear accident • Release from hospitals or nuclear facilities
	Air	• Released to air following a nuclear accident
	Water	• Leaching from surface soils to groundwaters

Decay modes





Average beta energy = 0.190 MeV
Total gamma energy = 0.38 MeV

Chemical properties/characteristics

Speciation	Analogue species
Iodine is a halogen element that exhibits a number of stable oxidation states. Two of the most important of these are the -1 (iodide) and +5 (iodate) compounds. Iodine can also take part in the formation of organic complexes.	There are chemical similarities between F, Cl, Br and I. However, I is an essential trace element that has specific biochemical roles and it has been extensively studied. Therefore, there is no need to rely on analogues to characterise its environmental behaviour.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Following deposition, I-131 will mainly be present on the external surfaces of plants. As iodine is not particularly particle reactive, I-131 present in soils will tend to migrate in surface or groundwaters through the terrestrial environment.	Because iodine is not particularly particle reactive, it will disperse freely in aquatic systems, although some binding to sediments can be expected.	Iodine released to the atmosphere may disperse as a vapour of the element, as an aerosol or as methyl iodide. Whereas elemental iodine and aerosol particles are efficiently deposited to surfaces, this is not the case for methyl iodide.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
I-131 mainly decays as it disperses through the environment. Iodine only exhibits a limited degree of sorption to mineral solids, but it can have a high affinity for organic matter.	I-131 will mainly be present on the external surfaces of plants, with some translocation to inner plant parts. It is highly bioavailable, being completely absorbed from the gastrointestinal tract of mammals and birds. Although short-lived, its half-life is long enough for it to be translocated to the thyroid. Iodine is only concentrated to a limited degree in most freshwater and marine organisms, with the exception of marine plants (e.g. some algae and seaweeds).

Effects on organisms

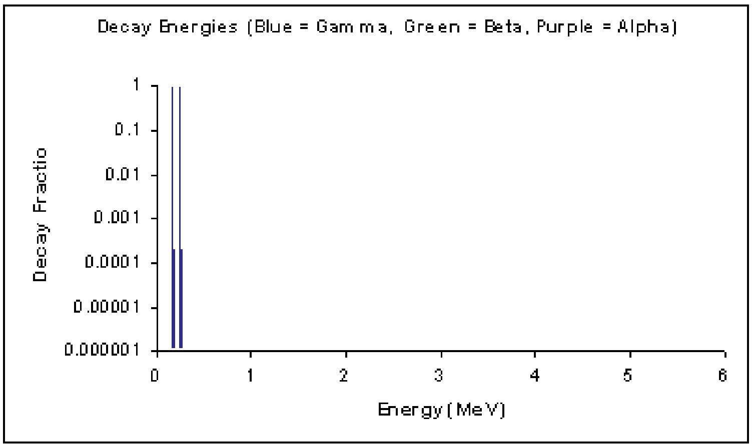
Dose effects/dosimetry	Species-specific considerations
I-131emits both beta particles and gamma rays. Because of its high degree of concentration in the thyroids of mammals and birds, radiation dose to the thyroid is of primary interest. At lower doses, thyroid cancer would be the effect of particular interest but, at very high doses, hypothyroidism might occur.	No major species-specific considerations, although it should be noted that uptake to the thyroid is strongly determined by the level of stable iodine present in the diet.

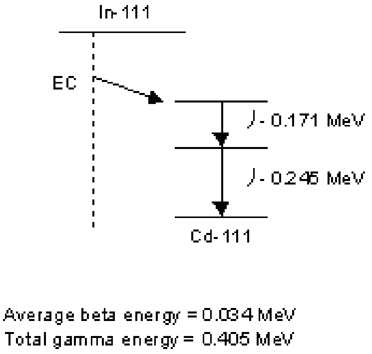
Name	Indium-111	*Symbol*	In-111	*Origin*	Activation
Radioactive half-life	2.8 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Cd-111	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor • Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• In medical diagnostics as a tool for studying the brain
Modes of release	Land	• Sewage sludge application to land, but would probably decay substantially before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Indium is a Group III element that can show oxidation states of +1 and +3. It forms ionic compounds with the halides (e.g. InF_3) and also forms an oxide. Indium dissolves in acids and is oxidised on heating in air.	No useful analogues for indium have been identified.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Little is known of the environmental behaviour of indium. However, it is not an essential trace element. With its short half-life, In-111 is likely to be retained on the external surfaces of plants.	No information is readily available on the behaviour of indium in aquatic environments.	If In-111 is released to the atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In terrestrial environments, In-111 is likely to decay close to its site of deposition. In aquatic environments, it will decay either in the water column or after deposition in bottom sediments.	There will be little uptake of In-111 by plants. Animals may ingest externally contaminated plants and soils. However, only limited uptake of In-111 is likely to occur (the fractional gastrointestinal absorption in rats is about 2 %). In-111 entering the systemic circulation is deposited mainly in bone marrow, liver kidneys and spleen.

Effects on organisms

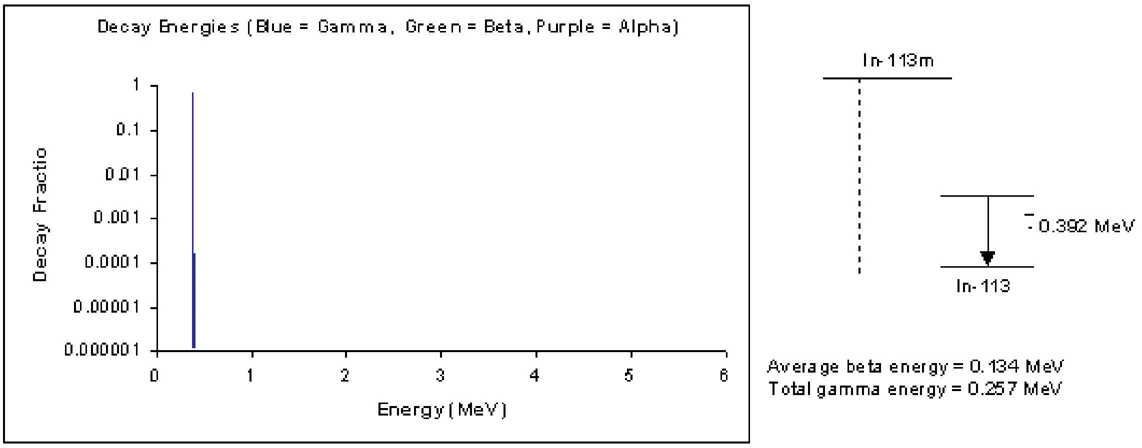
Dose effects/dosimetry	Species-specific considerations
In-111 emits mainly gamma rays. In view of its short half-life and low bioavailability, external irradiation is likely to be of greater importance than internal exposure of terrestrial plants and animals.	No species-specific considerations have been identified.

Name	Indium-113m	*Symbol*	In-113m	*Origin*	Activation
Radioactive half-life	1.7 hours	*Principal decay mode*	IT	*Grouping*	Artificial
Parent	N/A	*Daughter*	In-113	*Detection*	In situ

Production, uses and modes of release

Production		• Irradiation of stable precursors with neutrons in a nuclear reactor or cyclotron
Uses		• Diagnostic imaging of various parts of the body (liver, spleen, brain) • Determination of blood volume and cardiac output
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes



Chemical properties/characteristics

Speciation	Analogue species
Indium is a group III element that can show oxidation states of +1 and +3. It forms ionic compounds with the halides (e.g. InF_3) and also forms an oxide. Indium dissolves in acids and is oxidised on heating in air.	No useful analogues for indium have been identified.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Little is known of the environmental behaviour of indium. However, it is not an essential trace element.	No information is readily available on the behaviour of indium in aquatic environments.	If In-113m is released to the atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In terrestrial environments, In-113m is likely to decay close to its site of deposition. In aquatic environments, it will decay either in the water column or after deposition in bottom sediments.	There will be little uptake of In-113m by plants. Animals may ingest externally contaminated plants and soils. However, only limited uptake of In-113m is likely to occur (the fractional gastrointestinal absorption in rats is ~2 %). In-113m entering the systemic circulation is deposited mainly in bone marrow, liver kidneys and spleen.

Effects on organisms

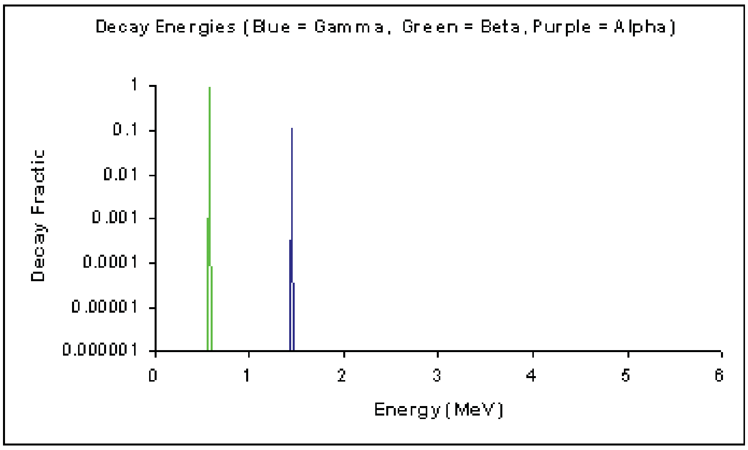
Dose effects/dosimetry	Species-specific considerations
In-113m emits gamma rays of energy 0.39 MeV. In view of its very short half-life and low bioavailability, external irradiation is likely to be of greater importance than internal exposure of terrestrial plants and animals.	No species-specific considerations have been identified.

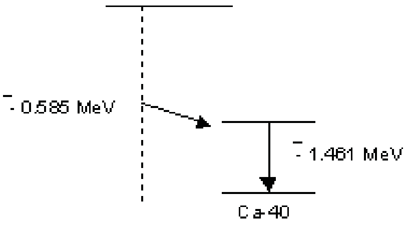
Name	Potassium-40	*Symbol*	K-40	*Origin*	Primordial
Radioactive half-life	1.3 x 10^9 years	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	N/A	*Daughter*	Ca-40	*Detection*	In situ

Production, uses and modes of release

Production		• Naturally during the formation of the universe
Uses		• No specific uses outside research activities
Modes of release	Land	• Present in all soils and rocks
	Air	• Not generally released to air
	Water	• Leaching via infiltration through to groundwater

Decay modes





Average beta energy = 0.523 MeV
Total gamma energy = 0.156 MeV

Chemical properties/characteristics

Speciation	Analogue species
Potassium is an alkali metal whose chemical behaviour is determined by the properties of the K^+ ion. Most of the compounds of potassium are ionic in nature, although more complex species can be formed. Potassium reacts extremely vigorously with water, oxygen and halogens.	K is a chemical analogue of Cs. However, as K is an essential element for all biota, except possibly a few bacteria, it is more appropriate to consider Cs by analogy with K than vice versa.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Little is known of the environmental behaviour of indium. However, it is not an essential trace element.	No information is readily available on the behaviour of indium in aquatic environments.	If In-113m is released to the atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In terrestrial environments, In-113m is likely to decay close to its site of deposition. In aquatic environments, it will decay either in the water column or after deposition in bottom sediments.	There will be little uptake of In-113m by plants. Animals may ingest externally contaminated plants and soils. However, only limited uptake of In-113m is likely to occur (the fractional gastrointestinal absorption in rats is ~2 %). In-113m entering the systemic circulation is deposited mainly in bone marrow, liver kidneys and spleen.

Effects on organisms

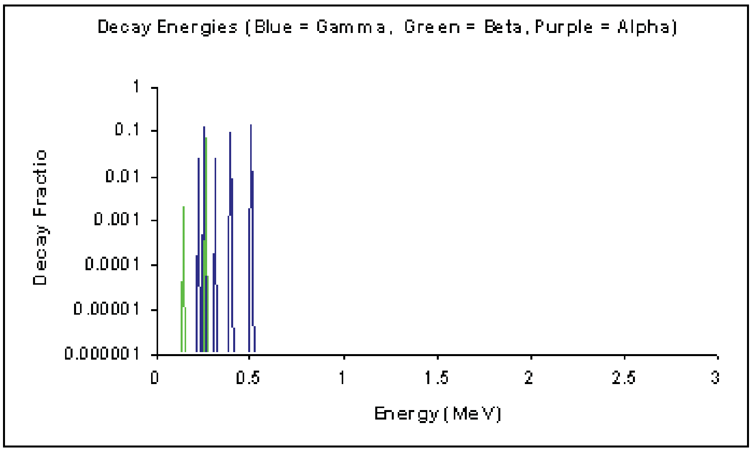
Dose effects/dosimetry	Species-specific considerations
In-113m emits gamma rays of energy 0.39 MeV. In view of its very short half-life and low bioavailability, external irradiation is likely to be of greater importance than internal exposure of terrestrial plants and animals.	No species-specific considerations have been identified.

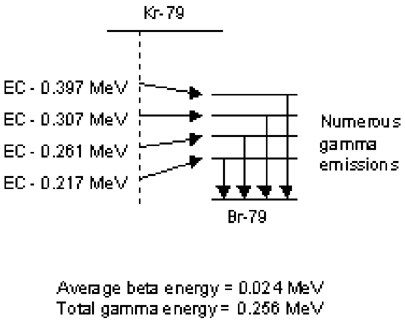
Name	Krypton-79	*Symbol*	Kr-79	*Origin*	Activation
Radioactive half-life	35 hours	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Br-79	*Detection*	Laboratory

Production, uses and modes of release

Production		• Neutron irradiation of stable precursors in a cyclotron or nuclear reactor
Uses		• Sometimes used as a gaseous industrial radiotracer
Modes	Land	• Not generally released to land
of	Air	• Industrial applications could result in some releases to air
release	Water	• Not generally released to water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Krypton is a noble gas and, as such, forms only a limited number of chemical compounds due to its lack of reactivity. One such example is KrF_2.	All the noble gases (Ne, Ar, Kr, Xe and Rn) exhibit similar environmental behaviour. Rn is a special case because it is generated in the environment from isotopes of radium and because it decays to produce chemically reactive, short-lived and long-lived radioactive progeny. For this reason, Rn should not be used as an analogue for Kr.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Kr-79 is not transferred significantly to the terrestrial environment.	Kr-79 is not transferred significantly to the aquatic environment.	Kr-79 is almost exclusively released to the atmosphere. Its very short radioactive half-life and low reactivity means that it decays almost entirely during atmospheric transport and is not transferred significantly to other environmental media.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
No major sink owing to its lack of reactivity and very short half-life.	Kr-79 is sparingly soluble in body tissues, notably those with a high fat content. However, it is not metabolised. Some Kr-79 will be present in the lungs in inhaled air.

Effects on organisms

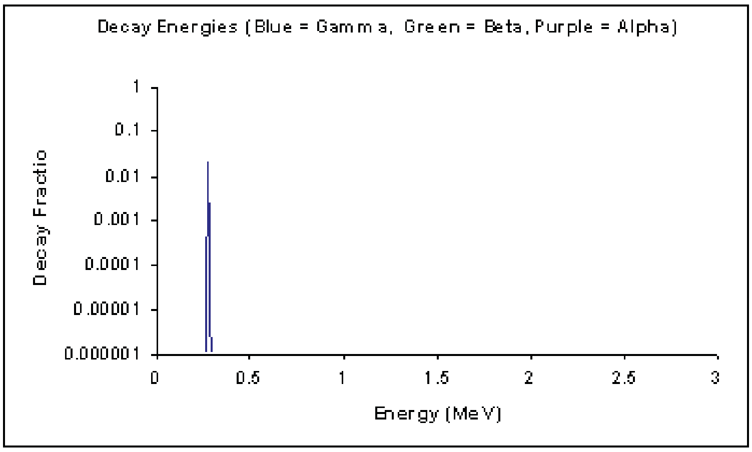
Dose effects/dosimetry	Species-specific considerations
Kr-79 emits mainly gamma rays, either directly or as positron-annihilation radiation. Radiation doses arise from: • external beta irradiation of superficial tissues of both plants and animals; • irradiation of the lungs of animals from contained gas and internal irradiation from gas dissolved in tissues.	Because the main consideration is external irradiation, there are no major species-dependent considerations. However, aquatic organisms, plant roots and burrowing animals will be shielded, to a greater or lesser degree, from such exposures.

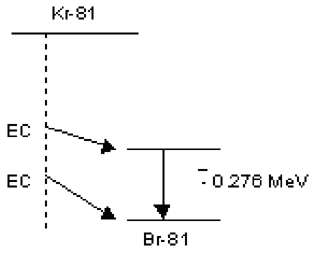
Name	Krypton-81	*Symbol*	Kr-81	*Origin*	Cosmogenic
Radioactive half-life	2.1 x 10^5 years	*Principal decay mode*	EC	*Grouping*	Natural
Parent	N/A	*Daughter*	Br-81	*Detection*	Laboratory

Production, uses and modes of release

Production		• From the decay of cyclotron-manufactured rubidium-81 • From the action of cosmic rays in the upper atmosphere
Uses		• The metastable species krypton-81m is used for lung ventilation scintigraphy
Modes of release	Land	• Not generally released to land
	Air	• Hospital applications could result in some releases to air
	Water	• Not generally released to water

Decay modes





Average beta energy = 0.005 MeV
Total gamma energy = 0.0118 MeV

Chemical properties/characteristics

Speciation	Analogue species
Krypton is a noble gas and lacks reactivity; as such, it forms only a limited number of chemical compounds. One such example is KrF_2.	All the noble gases (Ne, Ar, Kr, Xe and Rn) exhibit similar environmental behaviour. Rn is a special case because it is generated in the environment from isotopes of radium and because it decays to produce chemically reactive, short-lived and long-lived radioactive progeny. For this reason, Rn should not be used as an analogue for Kr.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Kr-81 is not transferred significantly to the terrestrial environment.	Kr-81 is not transferred significantly to the aquatic environment.	Kr-81 is almost exclusively released to, or generated in, the atmosphere. Its low reactivity means that it decays almost entirely in the atmosphere and is not transferred significantly to other environmental media.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
No major sink owing to its lack of reactivity.	Kr-81 is sparingly soluble in body tissues, notably those with a high fat content. However, it is not metabolised. Some Kr-81 will be present in the lungs in inhaled air.

Effects on organisms

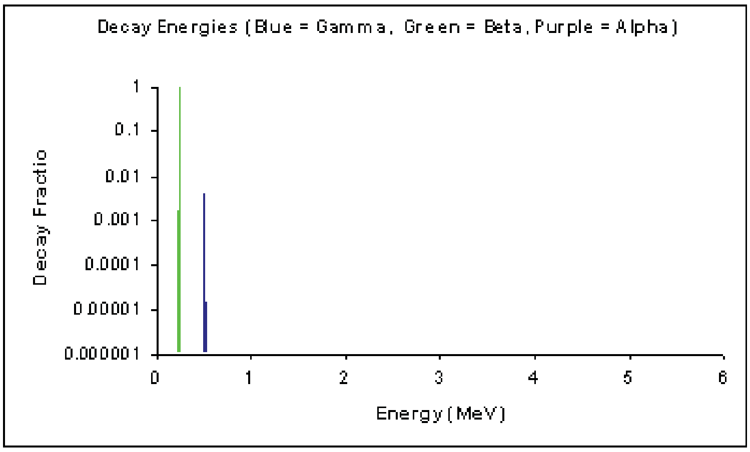
Dose effects/dosimetry	Species-specific considerations
Kr-81 is a weak gamma emitter. Exposures are mainly by external irradiation. Cosmogenic Kr-81 gives rise to negligible dose rates to organisms compared with other cosmogenic radionuclides such as C-14. Radiation doses arise from irradiation of the lungs of animals from contained gas and internal irradiation from gas dissolved in tissues.	As Kr-81 is globally dispersed in the atmosphere and is not accumulated in any environmental media, there are no major species-dependent considerations. However, aquatic organisms, plant roots and burrowing animals will be shielded, to a greater or lesser degree, from such exposures.

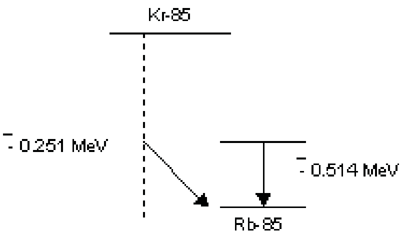
Name	Krypton-85	*Symbol*	Kr-85	*Origin*	Fission
Radioactive half-life	10.7 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Rb-85	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• No significant uses outside research activities
Modes	Land	• Not generally released to land
of	Air	• From fission reactors and reprocessing facilities
release	Water	• Not generally released to water

Decay modes





Average beta energy = 0.25 MeV
Total gamma energy = 0.002 MeV

Chemical properties/characteristics

Speciation	Analogue species
Krypton is a noble gas and, as such, forms only a limited number of chemical compounds due to its lack of reactivity. One such example is KrF_2.	All the noble gases (Ne, Ar, Kr, Xe and Rn) exhibit similar environmental behaviour. Rn is a special case because it is generated in the environment from isotopes of radium and because it decays to produce chemically reactive, short-lived and long-lived radioactive progeny. For this reason, Rn should not be used as an analogue for Kr.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Kr-85 is not transferred significantly to the terrestrial environment.	Kr-85 is not transferred significantly to the aquatic environment.	Kr-85 is almost exclusively released to the atmosphere. Its low reactivity means that it decays almost entirely in the atmosphere and is not transferred significantly to other environmental media.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
No major sink owing to its lack of reactivity.	Kr-85 is sparingly soluble in body tissues, notably those with a high fat content. However, it is not metabolised. Some Kr-85 will be present in the lungs in inhaled air.

Effects on organisms

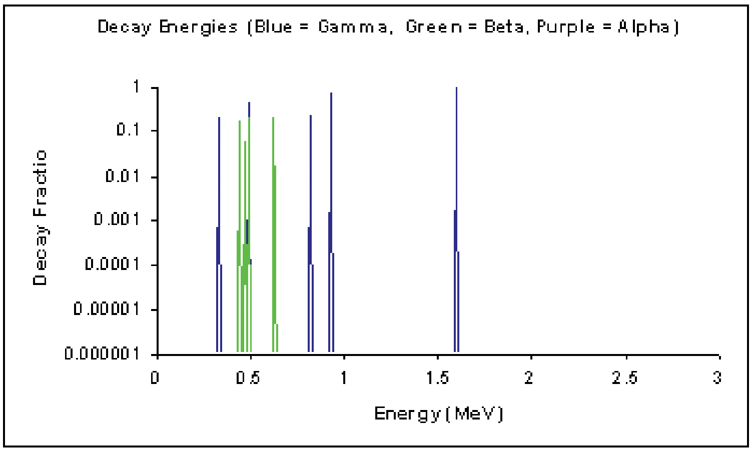
Dose effects/dosimetry	Species-specific considerations
Kr-85 is mainly a beta emitter, with a small component of gamma emission. Radiation doses arise from: • external beta irradiation of superficial tissues of both plants and animals; • irradiation of the lungs of animals from contained gas and internal irradiation from gas dissolved in tissues.	Because Kr-85 is not metabolised to any significant degree, there are no major species-dependent considerations.

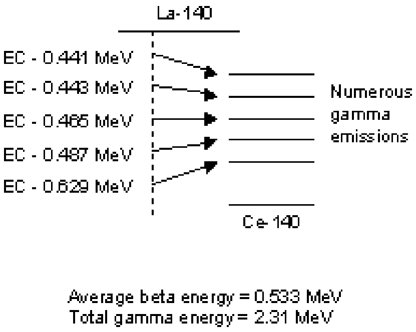
Name	Lanthanum-140	*Symbol*	La-140	*Origin*	Fission
Radioactive half-life	1.7 days	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Ce-140	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• Used in blast furnaces to measure residence times and to quantify furnace performance
Modes of release	Land	• Could be released to land following the disposal of ashes from furnaces
	Air	• Could enter the atmosphere in gaseous furnace wastes during burning
	Water	• Not generally released to water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Lanthanum is a rare earth element that shows an oxidation state of +3. As such, lanthanum forms compounds with hydrogen, oxygen and the halides. It also forms stable complexes.	The rare earth elements (Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu) exhibit similar chemical, biochemical and biogeochemical characteristics. However, these characteristics change systematically in the group with increasing atomic number. Cerium is one of the best-studied members of the group. Analogies with other members and higher actinides such as Am can be useful.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
La-140 is highly particle reactive, and hence would remain bound to soil particles and on the surfaces of plants. Transfers from plant to soil and bulk movement of soils would be the main transport mechanisms.	La-140 is highly particle reactive. It is likely to bind to suspended sediments and would migrate from the water column to bottom sediments by deposition.	If La-140 was released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The very short half-life and high particle reactivity of La-140 mean that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, bottom sediments close to the source of release may form an important sink.	Intake by terrestrial animals is likely to be mainly the ingestion of La-140 present on the exterior surfaces of plants or deposited on soil. La-140 is not very bioavailable to animals. The fractional gastrointestinal absorption is typically <0.1 %. Any La-140 that is absorbed is mainly deposited in the liver and skeleton. Very little uptake from the gastrointestinal tract is anticipated, except perhaps in pre-weaned animals. In the aquatic environment, uptake by fish and invertebrates is mainly direct from the water rather than food. Uptake by aquatic plants is likely to be by surface adsorption.

Effects on organisms

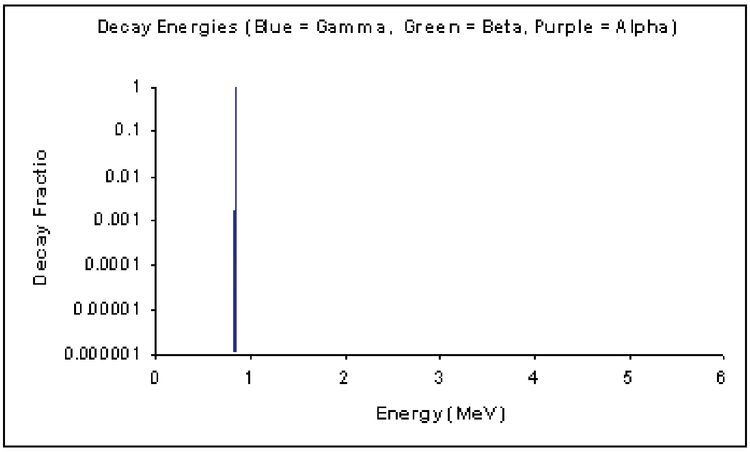
Dose effects/dosimetry	Species-specific considerations
La-140 emits energetic gamma photons. Because of its low bioavailability and very short half-life, external irradiation is more likely to be important than internal exposure.	In mammals and birds, the walls of the gastrointestinal tract are likely to receive substantially higher doses than other organs and tissues.

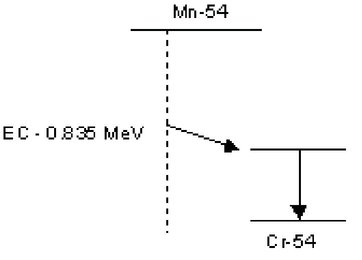
Name	Manganese-54	*Symbol*	Mn-54	*Origin*	Activation
Radioactive half-life	313 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Cr-54	*Detection*	In situ

Production, uses and modes of release

Production		• Produced by irradiating stable isotopes with neutrons or protons in a nuclear reactor or cyclotron
Uses		• Used to predict the behaviour of heavy metal components in effluents from mining waste water
Modes of release	Land	• Not generally released to land
	Air	• Could enter groundwater following mining water experiments
	Water	• Not generally released to air

Decay modes





Average beta energy = 0.004 MeV
Total gamma energy = 0.835 MeV

Chemical properties/characteristics

Speciation	Analogue species
Manganese is a transition element of Group VII that can show a wide range of oxidation states. Oxidation states +2 and +3 show the widest range of compounds. Manganese forms a range of oxides, including lower oxides (e.g. MnO) and higher oxides (manganates, e.g. MnO_4^-)	Although Mn has some chemical, biochemical and biogeochemical affinities with Cr, Fe and Tc, its high concentrations in the environment and its importance as an essential trace element mean that it is not appropriate to consider it as an analogue of any other element.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Mn-54 is moderately particle reactive in soils and sediments. It also tends to react with organic matter. Mn distributes relatively uniformly throughout plant tissues.	Mn-54 is highly particle reactive in aquatic environments. It will rapidly associate with suspended sediments.	If Mn-54 was released to atmosphere, it would be as an aerosol. MnO2 is the most likely form.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
As Mn-54 has a half-life of only 313 days and is moderately particle reactive, it can be expected to be retained in terrestrial soils and sediments, and to decay in situ. In the aquatic environment, Mn-54 will decay in bottom sediments close to its point of deposition.	Mn distributes relatively uniformly throughout plant tissues. Plant concentrations are similar to soil concentrations on a dry mass basis. Mn is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~5 %. However, it is well retained in the body, concentrating in the liver and bone. Very high concentration ratios relative to water are observed in all classes of marine organisms, ranging up to 10,000 or more. Concentration ratios in freshwater fish are rather lower, ranging up to about 500.

Effects on organisms

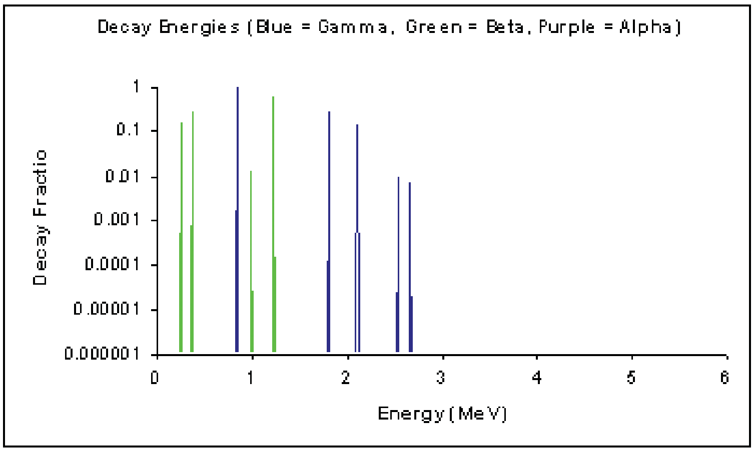
Dose effects/dosimetry	Species-specific considerations
The main emission from Mn-54 is an energetic gamma ray. Plants will be irradiated relatively uniformly from external and internal deposits of Mn-54. In animals, the long range of the emitted photon and significant uptake in other tissues means that most organs and tissues receive similar radiation doses.	The high concentration ratios exhibited by many aquatic organisms may mean that these are of particular interest.

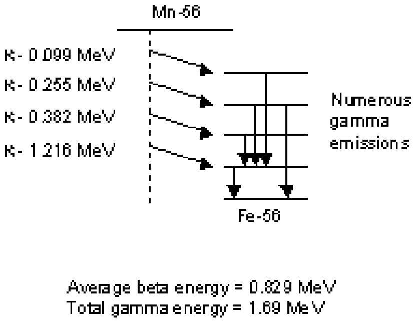
Name	Manganese-56	*Symbol*	Mn-56	*Origin*	Activation
Radioactive half-life	2.6 hours	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Fe-56	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of stable manganese present in reactor structures
Uses		• Occasionally as a radiotracer
Modes of release	Land	• Treatment and disposal of spent fuel and reactor hardware
	Air	• Treatment and disposal of spent fuel and reactor hardware
	Water	• Treatment and disposal of spent fuel and reactor hardware

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Manganese is a transition element of Group VII that can show a wide range of oxidation states. Oxidation states +2 and +3 show the widest range of compounds. Manganese forms a range of oxides, including lower oxides (e.g. MnO) and higher oxides (manganates, e.g. MnO_4^-)	Although Mn has some chemical, biochemical and biogeochemical affinities with Cr, Fe and Tc, its high concentrations in the environment and its importance as an essential trace element mean that it is not appropriate to consider it as an analogue of any other element.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Mn-56 is moderately particle reactive in soils and sediments. It also tends to react with organic matter. Mn distributes relatively uniformly throughout plant tissues.	Mn-56 is highly particle reactive in aquatic environments. It will rapidly associate with suspended sediments.	If Mn-56 was released to atmosphere, it would be as an aerosol. MnO2 is the most likely form.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Mn-56 deposited in the terrestrial environment would be expected to decay close to its point of deposition. Mn-56 in aquatic discharges would decay during transit to the surface water environment or shortly after discharge, either in the water column or in deposited sediments.	The very short half-life of Mn-56 means that it has little opportunity for uptake by either plants or animals.

Effects on organisms

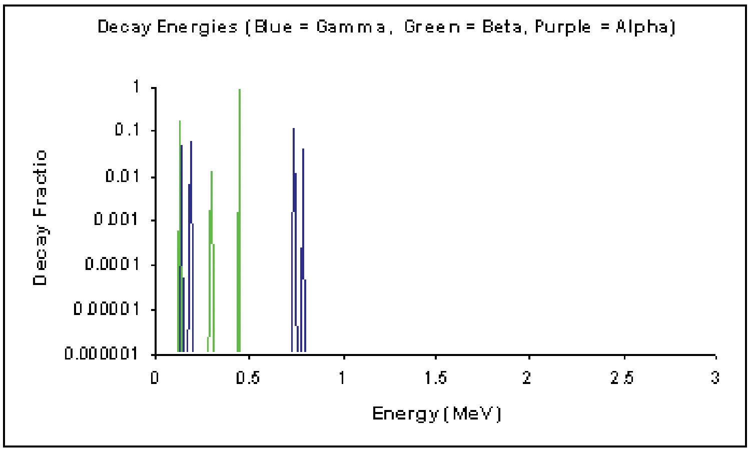
Dose effects/dosimetry	Species-specific considerations
Mn-56 is a beta-gamma emitter. The main consideration with Mn-56 in the terrestrial environment is external irradiation. In the aquatic environment, high external dose rates could occur due to trapping in deposited sediments close to the point of discharge.	No species-specific considerations, as the short half-life of Mn-56 means that there will be little opportunity for organisms to accumulate the radionuclide.

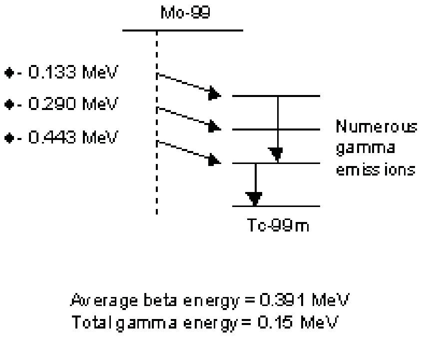
Name	Molybdenum-99	*Symbol*	Mo-99	*Origin*	Fission
Radioactive half-life	66 hours	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Tc-99m [R], Tc-99 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• During the fission process in a nuclear reactor
Uses		• To produce technetium-99 for medical applications
Modes of release	Land	• During treatment and disposal of spent fuel • Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air - some possible during treatment and disposal of spent fuel
	Water	• Not generally released to water - some possible during treatment and disposal of spent fuel • Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Molybdenum is a transition metal that shows all oxidation states from -2 through to +6. Molybdenum forms compounds with the halogens, oxygen and sulphur. It readily forms complexes with a wide range of atoms, most notably oxygen and sulphur.	Molybdenum is an essential trace element. It exhibits distinctive chemical and biochemical behaviour and it is inappropriate to identify an analogue.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Mo-99 is moderately particle reactive. Some transfer through the terrestrial environment can be expected in surface and groundwaters, but much will remain in situ. Mo-99 deposited on plants will be subject to a limited degree of foliar absorption.	Molybdenum in freshwaters is mainly present as dissolved species. In seawater, both dissolved and adsorbed Mo-99 could be present in similar quantities. In acid waters, Mo-99 may attach to colloidal particles of iron hydroxides.	If Mo-99 is released to atmosphere, it is likely to be as a liquid or solid aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In the terrestrial environment, Mo-99 will decay close to its point of deposition. In the aquatic environment, it will decay in the water column.	Although foliar absorption is thought to occur readily, the short half-life of Mo-99 will limit the degree to which it takes place. Mo-99 is highly available to animals, with a fractional gastrointestinal absorption of ~80 %. Although there is some preferential uptake in the skeleton, most Mo-99 will be relatively uniformly distributed throughout soft tissues. Concentration ratios for Mo relative to water are 10-100 in marine plants, around 1,000 in freshwater plants, from 1 to 100 in marine molluscs and around 10 in marine and freshwater fish.

Effects on organisms

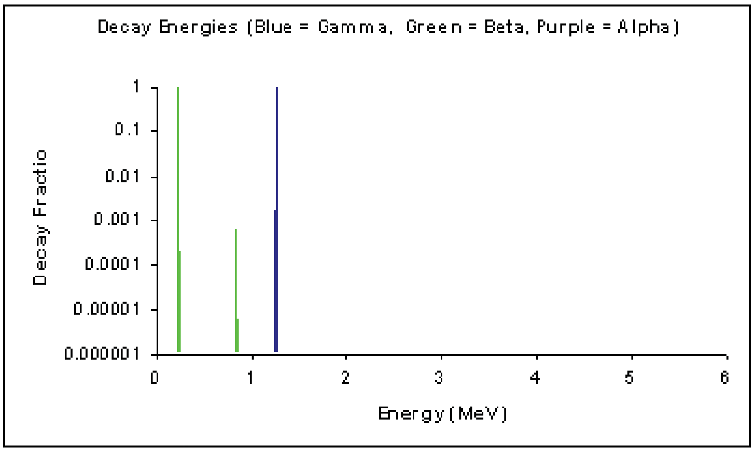
Dose effects/dosimetry	Species-specific considerations
Mo-99 will be present with Tc-99m in the environment. Beta and gamma emissions from these two radionuclides will generally give rise to relatively uniform internal whole-body exposures of all types of biota. External exposures from deposited Mo-99 and associated Tc-99m may also be of some significance in the terrestrial environment.	Tc-99m produced from Mo-99 decaying in the bodies of mammals and birds may have a tendency to translocate to the thyroid, following pathways of iodine metabolism. However, its short half-life and the inability of the thyroid to utilise it for hormone production will limit the significance of this pathway.

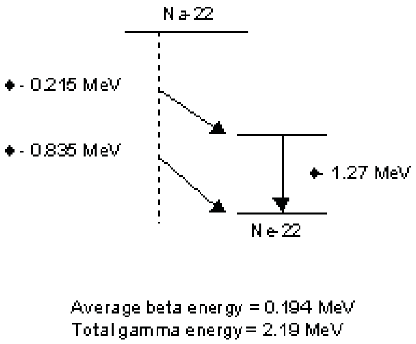
Name	Sodium-22	*Symbol*	Na-22	*Origin*	Cosmogenic
Radioactive half-life	2.6 years	*Principal decay mode*	Beta [gamma]	*Grouping*	Natural
Parent	N/A	*Daughter*	Ne-22	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• In medicine as a radiotracer and for diagnostic purposes
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Sodium is an alkali metal whose chemical behaviour is determined by the properties of the Na^+ ion. Most of the compounds of sodium are ionic in nature, although more complex species can be formed. Sodium reacts extremely vigorously with water, oxygen and halogens.	Na is an essential element for animals, but is less important for plants. Its chemistry, biochemistry and biogeochemistry are distinct from those of the other alkali metals (e.g. K) and it is inappropriate to consider it by analogy.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Sodium is moderately particle reactive. Therefore, it can be expected to remain largely in situ, although some dispersion through the terrestrial environment will occur.	The dominant form of sodium in waters is Na^+, but a limited degree of sorption to suspended sediments may occur. Nevertheless, Na-22 would be expected to behave conservatively in aquatic systems.	If Na-22 was released to the atmosphere, it would be in the form of an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Na-22 will migrate to some extent in the soil column and from terrestrial deposits to surface water bodies before decaying. However, the degree of movement will differ substantially in Na-rich and Na-deficient soils. In aquatic systems, Na-22 will decay mainly in the water column.	In terrestrial environments, high concentrations will occur in plants from active uptake. High concentrations may also occur in animals following ingestion of contaminated plant material or drinking water. Gastrointestinal absorption is virtually complete. Concentrations of Na-22 in plants and animals will tend to be higher in Na-deficient than in Na-rich conditions. A relatively high degree of uptake is expected in freshwater organisms, but not in marine organisms.

Effects on organisms

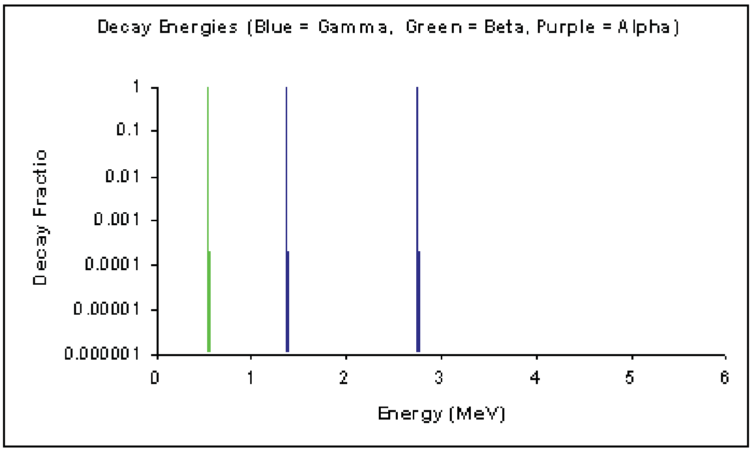
Dose effects/dosimetry	Species-specific considerations
Na-22 is a positron emitter. Thus, it emits annihilation gamma rays of energy 0.511 MeV, as well as a gamma ray of energy 1.275 MeV. These gamma rays mean that Na-22 can give rise to significant external exposure. However, its high bioavailability in terrestrial and freshwater environments means that internal exposures are likely to be more important.	Terrestrial plants and animals living in Na-deficient conditions need to be given special consideration. Freshwater organisms in environments in which the Na-22 is not rapidly dispersed and diluted should also be given special consideration.

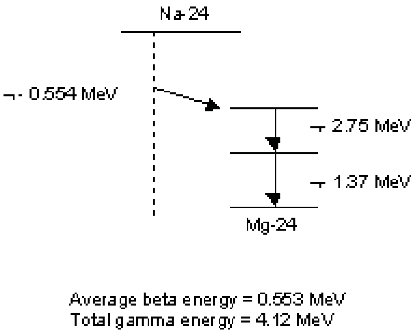
Name	Sodium-24	*Symbol*	Na-24	*Origin*	Cosmogenic
Radioactive half-life	15 hours	*Principal decay mode*	Beta [gamma]	*Grouping*	Natural
Parent	N/A	*Daughter*	Mg-24	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• In medicine as a radiotracer and for diagnostic purposes
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Sodium is an alkali metal whose chemical behaviour is determined by the properties of the Na^+ ion. Most of the compounds of sodium are ionic in nature, although more complex species can be formed. Sodium reacts extremely vigorously with water, oxygen and halogens.	Na is an essential element for animals, but is less important for plants. Its chemistry, biochemistry and biogeochemistry are distinct from those of the other alkali metals (e.g. K) and it is inappropriate to consider it by analogy.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Sodium is moderately particle reactive. Therefore, it can be expected to remain largely in situ, although some dispersion through the terrestrial environment will occur.	The dominant form of sodium in waters is Na^+, but a limited degree of sorption to suspended sediments may occur. Nevertheless, Na-24 would be expected to behave conservatively in aquatic systems.	If Na-24 was released to the atmosphere, it would be in the form of an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Na-24 will migrate to some extent in the soil column and from terrestrial deposits to surface water bodies before decaying. However, the very short half-life of Na-24 will limit the degree of migration. In aquatic systems, Na-24 will decay mainly in the water column.	In terrestrial environments, high concentrations will occur in plants from active uptake. High concentrations may also occur in animals following ingestion of contaminated plant material or drinking water. Gastrointestinal absorption is virtually complete. Concentrations of Na-24 in plants and animals will tend to be higher in Na-deficient than in Na-rich conditions. A relatively high degree of uptake is expected in freshwater organisms, but not in marine organisms.

Effects on organisms

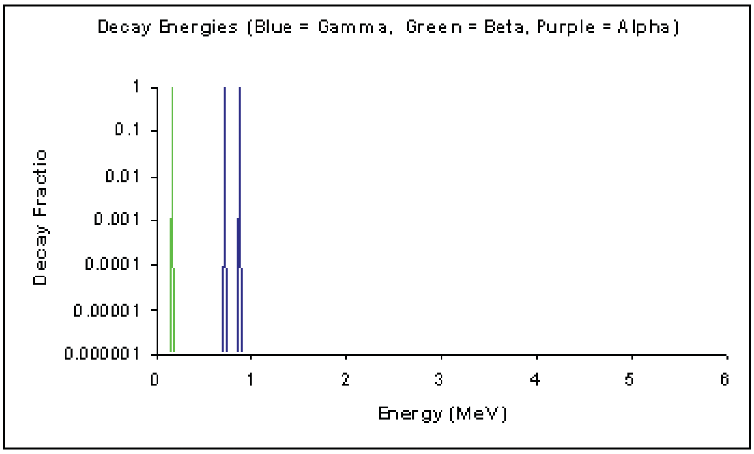
Dose effects/dosimetry	Species-specific considerations
Na-24 emits a beta particle and gamma rays with energies of 1.37 and 2.75 MeV. These gamma rays mean that Na-24 can give rise to significant external exposure. Because of its very short half-life, external exposure may be of more significance than internal exposure. However, the high bioavailability of Na-24 means that internal exposures must not be neglected.	Terrestrial plants and animals living in Na-deficient conditions need to be given special consideration. Freshwater organisms in environments in which the Na-24 is not rapidly dispersed and diluted should also be given special consideration.

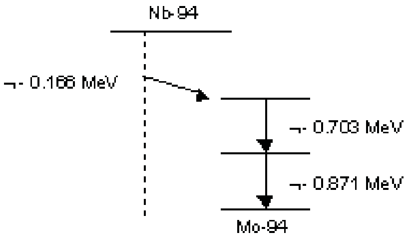
Name	Niobium-94	*Symbol*	Nb-94	*Origin*	Activation
Radioactive half-life	2.03 x 10^4 years	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Mo-94	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron irradiation of niobium-93 present in reactor components
Uses		• As a laboratory source of gamma rays
Modes of release	Land	• Treatment and disposal of spent fuel and reactor hardware
	Air	• Treatment and disposal of spent fuel and reactor hardware
	Water	• Treatment and disposal of spent fuel and reactor hardware

Decay modes





Average beta energy = 0.168 MeV
Total gamma energy = 1.57 MeV

Chemical properties/characteristics

Speciation	Analogue species
The chemistry of niobium is dominated by the +5 oxidation state. It forms halide compounds that hydrolyse easily to form niobium oxide, Nb_2O_5. The niobate ion (NbO_3^-) can also be formed by reducing niobium oxide. Niobium can also take part in the formation of colloids and organic complexes.	Na is an essential element for animals, but is less important for plants. Its chemistry, biochemistry and biogeochemistry are distinct from those of the other alkali metals (e.g. K) and it is inappropriate to consider it by analogy.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Nb-94 is moderately particle reactive in terrestrial soils. It is strongly excluded from plants. The little Nb-94 that is taken up by roots is mainly retained there and not translocated to above ground tissues.	Nb-94 is highly particle reactive in aquatic sediments. It will rapidly associate with suspended sediments.	If Nb-94 is released to atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In terrestrial environments, Nb-94 will mainly be retained in the soil column. In aquatic environments, most Nb-94 is likely to become adsorbed to suspended sediments and hence migrate to bottom sediments.	Nb-94 is not very bioavailable to plants. Animal intakes are likely to result mainly from the ingestion of soil or of contaminated drinking water. The fractional gastrointestinal absorption is ~0.2 %, except in pre-weaned animals. Much of the uptake is deposited in mineral bone, with the remainder widely dispersed amongst soft tissues. Concentration ratios relative to water are ~30 for freshwater and marine fish. Concentration ratios for marine molluscs and crustaceans are typically ~200 and ~1,000, respectively. Concentration ratios for marine plants are also ~1,000.

Effects on organisms

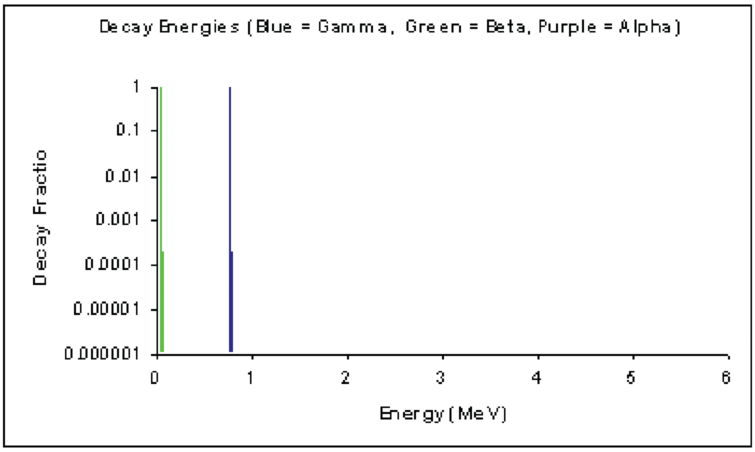
Dose effects/dosimetry	Species-specific considerations
Nb-94 is a beta-gamma emitter. External exposure is likely to be of greater importance than internal exposure in many contexts, notably in the terrestrial environment.	Special consideration should be given to marine molluscs, crustaceans and plants in view of the concentration ratios for these species.

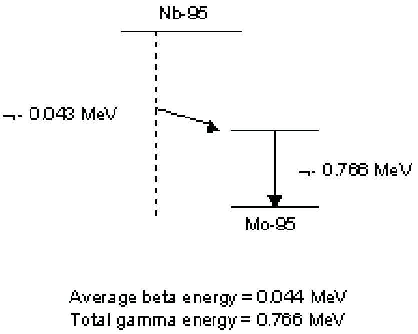
Name	Niobium-95	*Symbol*	Nb-95	*Origin*	Radiogenic
Radioactive half-life	35 days	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	Zr-95	*Daughter*	Mo-95	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor • From the decay of Zr-95, also an important fission product
Uses		• No significant uses outside research activities
Modes of release	Land	• During treatment and disposal of spent fuel
	Air	• Not generally released to air
	Water	• During treatment and disposal of spent fuel • Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The chemistry of niobium is dominated by the +5 oxidation state. It forms halide compounds that hydrolyse easily to form niobium oxide, Nb_2O_5. The niobate ion (NbO_3^-) can also be formed by reducing niobium oxide. Niobium can also take part in the formation of colloids and organic complexes.	Zr and Nb have been quite extensively studied. They exhibit considerable similarities in their environmental behaviour.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Nb-95 is moderately particle reactive in terrestrial soils. It is strongly excluded from plants. The little Nb-95 that is taken up by roots is mainly retained there and not translocated to above ground tissues.	Nb-95 is highly particle reactive in aquatic sediments. It will rapidly associate with suspended sediments.	If Nb-95 is released to atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In terrestrial environments, Nb-95 will mainly be retained in the soil column. In aquatic environments, most Nb-95 is likely to become adsorbed to suspended sediments and hence migrate to bottom sediments.	Nb-95 is not very bioavailable to plants. Animal intakes are likely to result mainly from the ingestion of soil or of contaminated drinking water. The fractional gastrointestinal absorption is ~0.2 %, except in pre-weaned animals. Much of the uptake is deposited in mineral bone, with the remainder widely dispersed amongst soft tissues. Concentration ratios relative to water are ~30 for freshwater and marine fish. Concentration ratios for marine molluscs and crustaceans are typically ~200 and ~1,000, respectively. Concentration ratios for marine plants are also ~1,000.

Effects on organisms

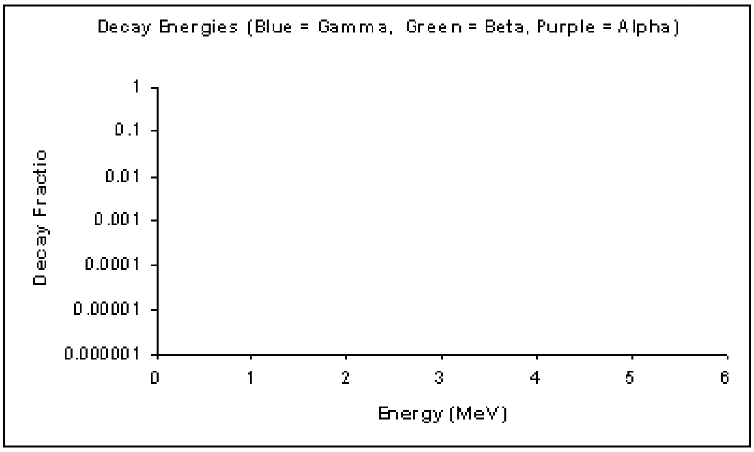
Dose effects/dosimetry	Species-specific considerations
Nb-95 is a beta-gamma emitter. External exposure is likely to be of greater importance than internal exposure in many contexts, notably in the terrestrial environment.	Because of its low bioavailability and the importance of external irradiation, there are no major species-specific considerations. However, special consideration should be given to benthic aquatic organisms located close to sources of aquatic release, as these may be exposed to high Nb-95 concentrations in deposited sediments.

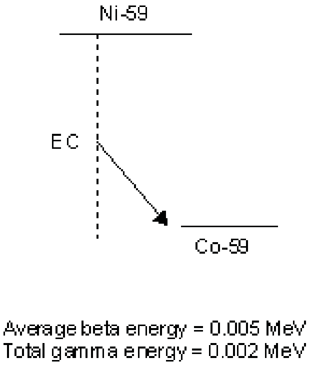
Name	Nickel-59	*Symbol*	Ni-59	*Origin*	Cosmogenic
Radioactive half-life	7.6×10^4 years	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	N/A	*Daughter*	Co-59	*Detection*	Laboratory

Production, uses and modes of release

Production		• Fission neutron irradiation of metallic nuclear reactor components (e.g. Cr, Mn, Fe, Co, Ni) • Cosmic ray interactions in the upper atmosphere
Uses		• No specific uses outside research activities
Modes of release	Land	• Treatment and disposal of spent fuel hardware
	Air	• Treatment and disposal of spent fuel hardware • Trace amounts due to fallout from weapons testing
	Water	• Treatment and disposal of spent fuel hardware

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Nickel is a transition metal that can exist in a number of oxidation states. The +2 state is the most stable in terms of the properties of the compounds for variations in pH and Eh. Such compounds include the halides, hydroxide and carbonate.	There are chemical, biochemical and biogeochemical similarities amongst a number of the transition metals. However, Ni is an essential trace element in some species and its environmental behaviour has been extensively studied. Therefore, it is not necessary or appropriate to rely on analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ni is moderately particle reactive in soils and is unlikely to be available for uptake by plants.	Ni is highly particle reactive in both freshwaters and marine environments. Significant migration to deposited sediments is likely to occur in both types of environment.	If Ni-59 is released to the atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Although Ni-59 will be moderately well retained in soils, its long half-life means that there will eventually be significant transfer to aquatic environments by leaching and erosive processes. In the aquatic environment, most Ni-59 is likely to eventually be present in deposited sediments, which is where it will mainly decay.	Ni-59 is not particularly bioavailable to plants. Intakes by animals in terrestrial environments will be of Ni-59 incorporated in plants, bound to soil and in drinking water. Ni is not very bioavailable to animals, with a fractional gastrointestinal absorption of ~5 %. That which is not rapidly excreted becomes uniformly distributed in the body and tenaciously retained. Concentration ratios relative to water are typically ~100 for freshwater and marine fish, and ~1,000 for marine plants, molluscs and crustaceans.

Effects on organisms

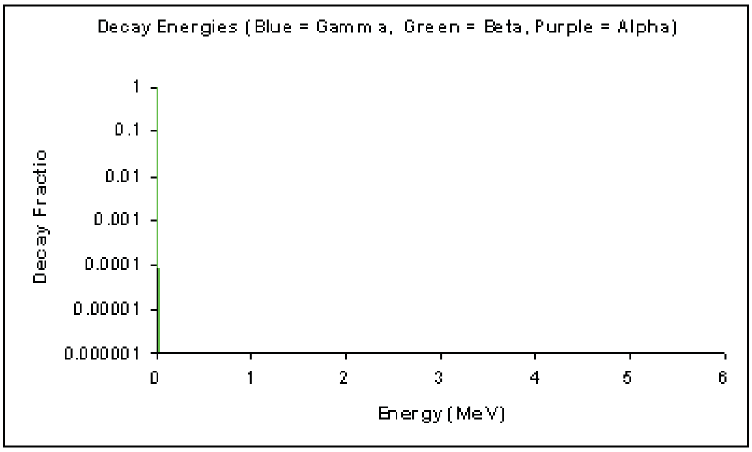
Dose effects/dosimetry	Species-specific considerations
Ni-59 emits low energy X-rays and electrons. This means that external irradiation is of little importance. Ni-59 incorporated into organisms is distributed relatively uniformly throughout them. Doses to individual organs and tissues will thus be of similar magnitude to average whole-body doses.	No major species-specific considerations have been identified. However, special consideration should be given to benthic organisms located close to sources of aquatic release, as these may be exposed to high Ni-59 concentrations in aquatic sediments and take up Ni-59 from those sediments.

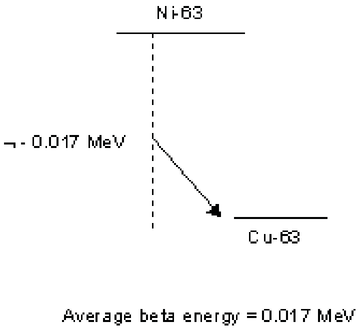
Name	Nickel-63	*Symbol*	Ni-63	*Origin*	Activation
Radioactive half-life	100 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Cu-63	*Detection*	Laboratory

Production, uses and modes of release

Production		• Fission neutron irradiation of metallic nuclear reactor components (e.g. Cr, Mn, Fe, Co, Ni)
Uses		• No specific uses outside research activities
Modes of release	Land	• Treatment and disposal of spent fuel hardware
	Air	• Treatment and disposal of spent fuel hardware • Trace amounts due to fallout from weapons testing
	Water	• Treatment and disposal of spent fuel hardware

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Nickel is a transition metal that can exist in a number of oxidation states. The +2 state is the most stable in terms of the properties of the compounds for variations in pH and Eh. Such compounds include the halides, hydroxide and carbonate.	There are chemical, biochemical and biogeochemical similarities amongst a number of the transition metals. However, Ni is an essential trace element in some species and its environmental behaviour has been extensively studied. Therefore, it is not necessary or appropriate to rely on analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ni is moderately particle reactive in soils and little added Ni-63 is likely to remain available for uptake by plants.	Ni is highly particle reactive in both freshwaters and marine environments. Significant migration to deposited sediments is likely to occur in both types of environment.	If Ni-63 is released to the atmosphere, it is likely to be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Although Ni-63 will be moderately well retained in soils, its long half-life means that there will eventually be significant transfer to aquatic environments by leaching and erosive processes. In the aquatic environment, most Ni-63 is likely to eventually be present in deposited sediments, which is where it will mainly decay.	Ni-63 is not particularly bioavailable to plants. Intakes by animals in terrestrial environments will be of Ni-63 incorporated in plants, bound to soil and in drinking water. Ni is not very bioavailable to animals, with a fractional gastrointestinal absorption of around 5 %. That which is not rapidly excreted becomes uniformly distributed in the body and tenaciously retained. Concentration ratios relative to water are typically ~100 for freshwater and marine fish, and ~1,000 for marine plants, molluscs and crustaceans.

Effects on organisms

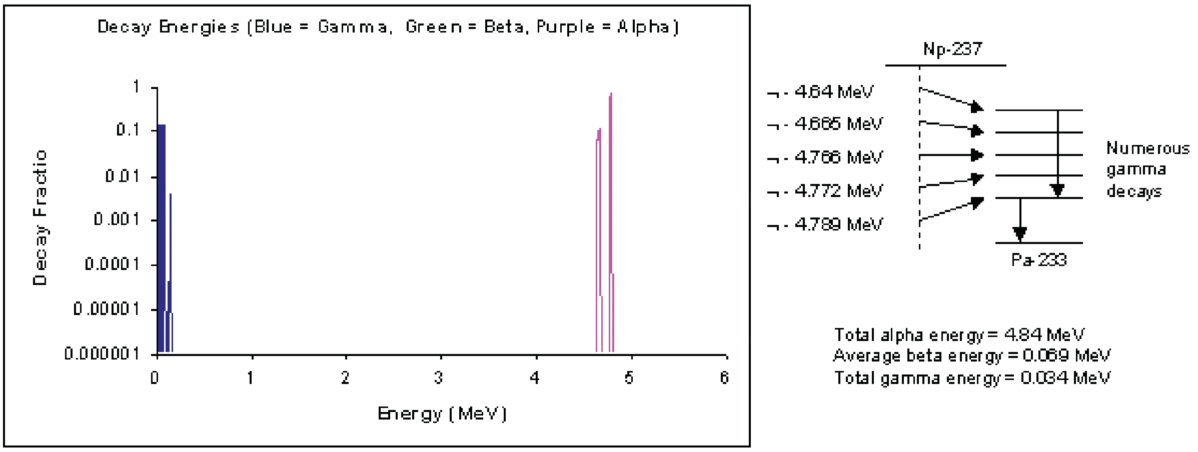
Dose effects/dosimetry	Species-specific considerations
Ni-63 emits low-energy beta particles. This means that external irradiation is of little importance. Ni-63 incorporated into organisms is distributed relatively uniformly throughout them. Doses to individual organs and tissues will thus be of similar magnitude to average whole-body doses.	No major species-specific considerations have been identified. However, special consideration should be given to benthic organisms located close to sources of aquatic release, as these may be exposed to high Ni-63 concentrations in aquatic sediments and take up Ni-63 from those sediments.

Name	Neptunium-237	*Symbol*	Np-237	*Origin*	Breeding
Radioactive half-life	2.1 x 10^6 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Am-241	*Daughter*	Pa-233 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Trace quantities found in nature • Decay of americium-241 produced in a nuclear reactor
Uses		• Sometimes used in neutron detection equipment
Modes of release	Land	• Treatment and disposal of spent fuel
	Air	• Not generally released to air
	Water	• Treatment and disposal of spent fuel

Decay modes



Chemical properties/characteristics

Speciation	Analogue species
Neptunium can exist in a number of oxidation states, but only the +4 and +5 states are important in environmental systems. A variety of species in aqueous solution can be formed, depending on Eh and pH.	There are chemical similarities between Np and U, and also between Np and Pu. However, the chemistry, biochemistry and biogeochemistry of Np are complex, and neither U nor Pu can be relied upon as quantitative analogues for its behaviour in the environment.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Np-237 is moderately particle reactive in terrestrial soils and sediments. Most Np-237 will therefore remain in situ.	Np-237 is highly particle reactive in the aquatic environment and therefore tends to migrate to bottom sediments.	Np-237 would be expected to disperse as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Np-237 deposited in the terrestrial environment will mainly be transferred to soils, where it will tend to remain. In aquatic systems, bottom sediments are the most likely environmental sink and Np-237 migration will be closely associated with sediment transport.	Np-237 is quite strongly excluded from plants. Much of the Np-237 content of plants is likely to be due to surface contamination. Ingestion of contaminated soil or sediment and inhalation could compete with ingestion of contaminated plant material as important routes of intake by animals. Uptake from the gastrointestinal tract is limited (typically ~0.001), although enhanced concentrations of Np-237 may occur in the liver, kidneys and skeleton. Concentration ratios of between 10 and 100 are typical for marine and freshwater species.

Effects on organisms

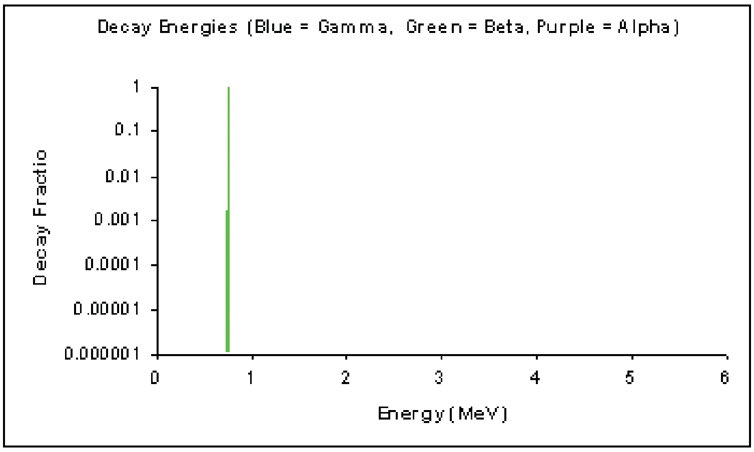
Dose effects/dosimetry	Species-specific considerations
Ni-63 emits low-energy beta particles. This means that external irradiation is of little importance. Ni-63 incorporated into organisms is distributed relatively uniformly throughout them. Doses to individual organs and tissues will thus be of similar magnitude to average whole-body doses.	No major species-specific considerations have been identified. However, special consideration should be given to benthic organisms located close to sources of aquatic release, as these may be exposed to high Ni-63 concentrations in aquatic sediments and take up Ni-63 from those sediments.

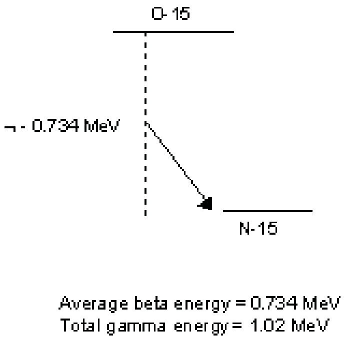
Name	Oxygen-15	*Symbol*	O-15	*Origin*	Activation
Radioactive half-life	122 seconds	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	N-15	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced by irradiating stable precursors in a cyclotron
Uses		• Used in positron emission tomography to study brain physiology and pathology
Modes of release	Land	• Not generally released to land
	Air	• Could be released to air, but the very short half-life mitigates any adverse impact
	Water	• Not generally released to water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The predominant oxidation state for oxygen is -2. It is an extremely reactive gas and is capable of forming compounds with most other elements, usually forming one or more oxides of those elements.	Oxygen is a ubiquitous element in the environment and is involved in a wide variety of biological, biochemical and biogeochemical processes. There is no appropriate analogue, but the environmental behaviour of the stable element has been extensively studied.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
The half-life of O-15 is too short for significant transport in the terrestrial environment to occur.	The half-life of O-15 is too short for significant transport in the aquatic environment to occur.	O-15 has a radioactive half-life of only 122 seconds. Therefore, the only potentially relevant pathway is atmospheric release and exposure from the dispersing plume. Dispersion distances before the activity is substantially depleted by radioactive decay will be no more than a few kilometres.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
O-15 released to the atmosphere will decay as it disperses.	The main uptake mechanism for O-15 is inhalation, although any O-15 that is absorbed by organisms will decay rapidly.

Effects on organisms

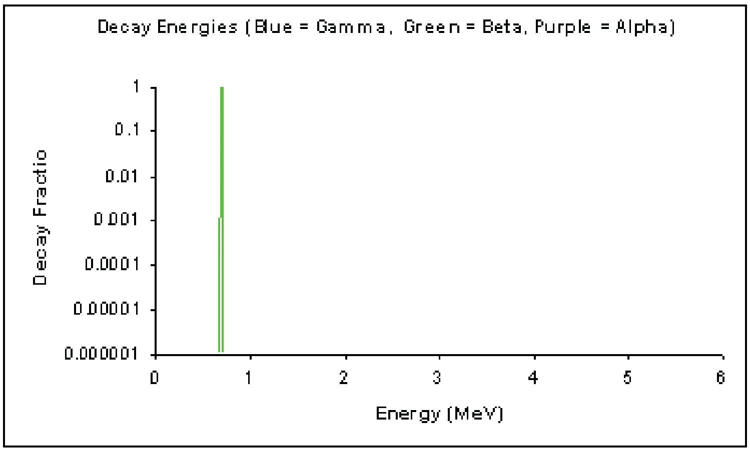
Dose effects/dosimetry	Species-specific considerations
The 0.511 MeV photons from O-15 will give rise to whole-body exposure from external irradiation. Positron emissions can also give rise to superficial exposures to organisms, but this is likely to be a secondary consideration.	Because the main consideration is external irradiation, there are no major species-dependent considerations. However, aquatic organisms, plant roots and burrowing animals will be shielded, to a greater or lesser degree, from such exposures.

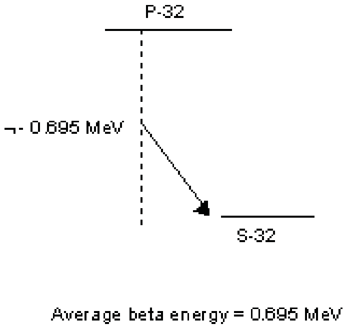
Name	Phosphorus-32	*Symbol*	P-32	*Origin*	Activation
Radioactive half-life	14.3 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	S-32	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced by irradiating stable precursors in a cyclotron
Uses		• Used in positron emission tomography to study brain physiology and pathology
Modes of release	Land	• Not generally released to land
	Air	• Could be released to air, but the very short half-life mitigates any adverse impact
	Water	• Not generally released to water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Phosphorus is a Group V element that shows two stable oxidation states, +3 and +5. Phosphorus forms compounds with the halides, hydrogen, oxygen and sulphur, and forms a range of organic acids. Phosphorus can be obtained in a number of allotropic forms, of which white phosphorus is the most reactive.	Oxygen is a ubiquitous element in the environment and is involved in a wide variety of biological, biochemical and biogeochemical processes. There is no appropriate analogue, but the environmental behaviour of the stable element has been extensively studied.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Phosphorus shows only limited particle reactivity, and so can be expected to move freely through the terrestrial environment, rather than remaining in situ.	In aquatic ecosystems, phosphorus is present as particulate organic phosphorus, dissolved inorganic phosphates and dissolved organic phosphorus. In most aquatic environments, particulate phosphorus is in greatest abundance.	If P-32 were released to the atmosphere, it would probably be in the form of an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
P-32 is sufficiently short-lived that it will decay close to its site of deposition in the terrestrial environment. In the aquatic environment, P-32 is likely to decay mainly in the water column, either in solution or incorporated in organic particles.	P-32 deposited on land is likely to be highly available to plants, as soils typically contain only 0.65 ppm but plants contain about 1,000 ppm. It is highly available to animals, with gastrointestinal absorption being almost complete. In the short-term, phosphorus is widely distributed throughout all tissues. In the long-term, calcified tissues are the main reservoir. In aquatic environments, very rapid uptake by organisms can be expected, leading to concentration ratios relative to water of 10,000 or more.

Effects on organisms

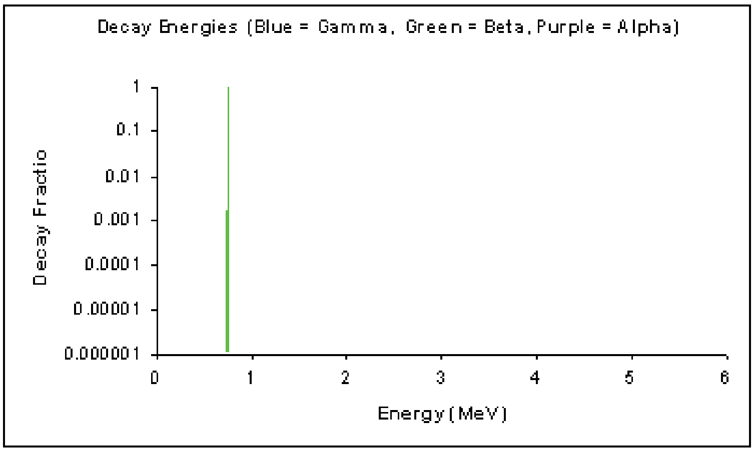
Dose effects/dosimetry	Species-specific considerations
P-32 is a pure beta emitter. Because of this and its high bioavailability, internal exposures will be of principal importance. Although there may be some degree of preferential irradiation of calcified tissues, the effect will be limited by the short half-life of the radionuclide.	No major species-specific considerations have been identified.

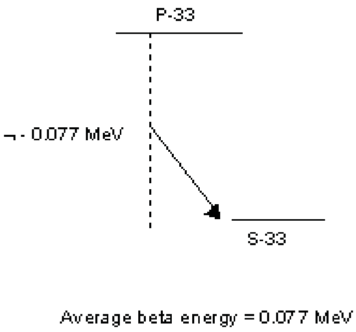
Name	Phosphorus-33	*Symbol*	P-33	*Origin*	Activation
Radioactive half-life	25.3 days	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	N/A	*Daughter*	S-33	*Detection*	Laboratory

Production, uses and modes of release

Production		• Neutron bombardment of stable sulphur-33 in a cyclotron
Uses		• In medicine as a radiotracer
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Phosphorus is a Group V element that shows two stable oxidation states, +3 and +5. Phosphorus forms compounds with the halides, hydrogen, oxygen and sulphur, and forms a range of organic acids. Phosphorus can be obtained in a number of allotropic forms, of which white phosphorus is the most reactive.	Phosphorus as phosphate is essential to all living cells and is a component of DNA. For this reason, it is appropriately considered in its own right, rather than as an analogue of any other element.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Phosphorus shows only limited particle reactivity, and so can be expected to move freely through the terrestrial environment, rather than remaining in situ.	In aquatic ecosystems, phosphorus is present as particulate organic phosphorus, dissolved inorganic phosphates and dissolved organic phosphorus. In most aquatic environments, particulate phosphorus is in greatest abundance.	If P-33 were released to the atmosphere, it would probably be in the form of an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
P-33 is sufficiently short-lived that it will decay close to its site of deposition in the terrestrial environment. In the aquatic environment, P-33 is likely to decay mainly in the water column, either in solution or incorporated in organic particles.	P-33 deposited on land is likely to be highly available to plants, as soils typically contain only 0.65 ppm but plants contain about 1,000 ppm. It is highly available to animals, with gastrointestinal absorption being almost complete. In the short-term, phosphorus is widely distributed throughout all tissues. In the long-term, calcified tissues are the main reservoir. In aquatic environments, very rapid uptake by organisms can be expected, leading to concentration ratios relative to water of 10,000 or more.

Effects on organisms

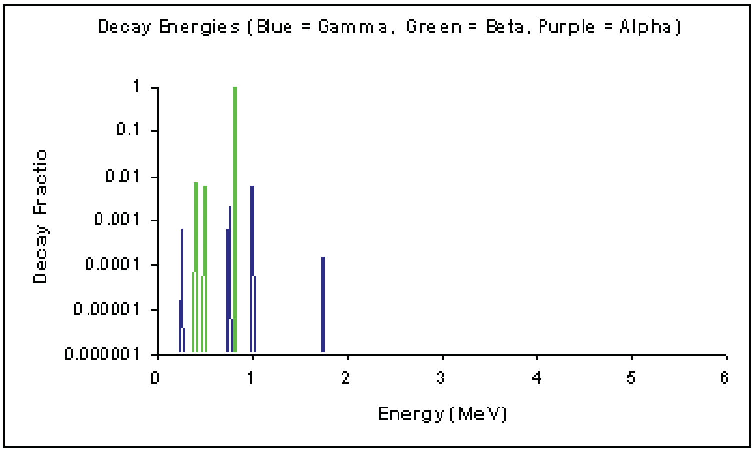
Dose effects/dosimetry	Species-specific considerations
P-33 is a pure beta emitter. Because of this and its high bioavailability, internal exposures will be of principal importance. Although there may be some degree of preferential irradiation of calcified tissues, the effect will be limited by the short half-life of the radionuclide.	No major species-specific considerations have been identified.

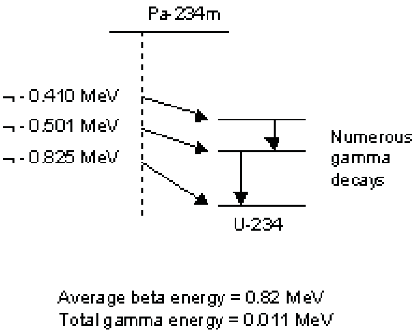
Name	Protactinium-234m	*Symbol*	Pa-234m	*Origin*	Radiogenic
Radioactive half-life	1.2 minutes	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	Th-234	*Daughter*	U-234 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Naturally in all environmental media from the decay of U-238
Uses		• No specific uses outside research activities
Modes of release	Land	• Disposed uranium mill tailings
	Air	• Only in circumstances where U-238/Th-234 is present in air
	Water	• Only in circumstances where U-238/Th-234 is present in water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Protactinium exists in aqueous solution in two oxidation states, +4 and +5, although the +5 state tends to be predominant. Protactinium compounds tend to hydrolyse in solution. Pa is not usually found in solution as a single species, but appears as a mixture of complexes and hydrolysed species.	Pa-234m has a half-life of only 1.2 minutes and will have little time to exhibit its environmental chemistry. Therefore, there is no need to identify analogue species.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pa-234m would be expected to be present at close to the same activity equilibrium as its parent Th-234.	Pa-234m would be expected to be present at close to the same activity concentration as its parent Th-234. Th is particle reactive.	Pa-234m would be expected to be present in aerosols at close to the same activity concentration as its parent Th-234.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Pa-234m would be expected to decay close to its site of production.	Because of its very short half-life, Pa-234m would be present in biota at close to the same activity concentration as its parent Th-234. Therefore, intake and uptake of Pa-234m are of little relevance compared with intake and uptake of its parent, Th-234.

Effects on organisms

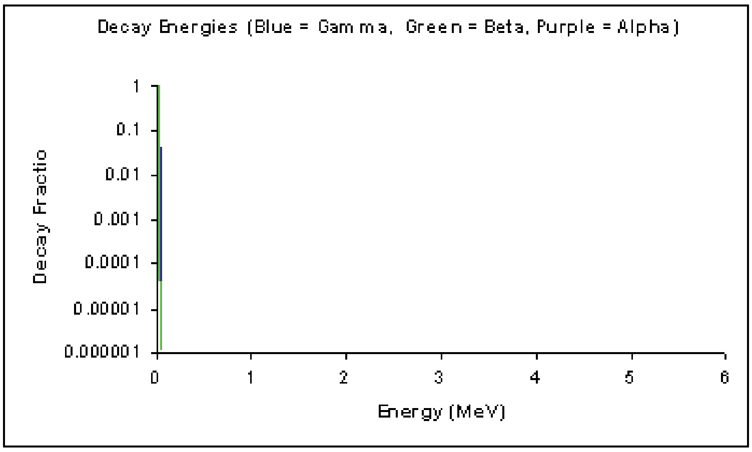
Dose effects/dosimetry	Species-specific considerations
Pa-234m is mainly a beta emitter, although there is also a small amount of gamma emission. Therefore, it is mainly of interest as an internally incorporated radionuclide, as it will deliver more dose than its parent Th-234.	No species-specific considerations have been identified.

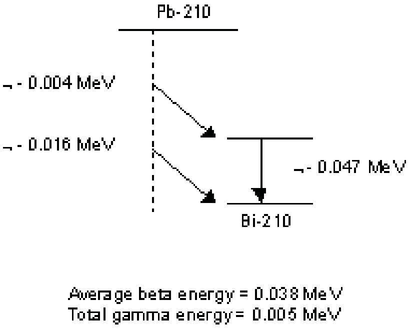
Name	Lead-210	*Symbol*	Pb-210	*Origin*	Radiogenic
Radioactive half-life	22.3 years	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	Po-214	*Daughter*	Bi-210 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Naturally in all environmental media from the decay of U-238 • By product of uranium mining and milling
Uses		• Determination of the age of lake and ocean sediments
Modes of release	Land	• Fallout from atmosphere following the decay of Rn-222
	Air	• From burning coal • From decay in the atmosphere of Rn-222
	Water	• Fallout from atmosphere following the decay of Rn-222

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Lead is found predominantly in the +2 oxidation state in environmental waters. It exists primarily as carbonato-, hydroxy- and chloro- complexes. Lead also forms compounds with oxygen, the halides and various organic molecules.	There are similarities between the chemistry and biochemistry of Pb and Ca. These can be useful mainly for interpretation of specific observations on Pb, rather than treating Pb as behaving in a generally analogous manner to Ca throughout the environment.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pb-210 shows a very high level of particle reactivity, and so can be expected to remain in situ, rather than moving freely through the terrestrial environment.	Pb-210 is produced in aquatic systems from the decay of Ra-226 via Rn-222 and its short-lived progeny. Owing to its particle reactivity, it will tend to bind to sediments.	Pb-210 is produced in the atmosphere mainly from the progeny of Rn-222. It is then subject to deposition.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In terrestrial systems, Pb-210 typically decays close to its site of production. In aquatic systems, Pb-210 tends to accumulate in bottom sediments	Pb-210 accumulates mainly on the external surfaces of plants, as it exhibits only a limited degree of bioavailability. Lichens have very large surface areas per unit area of ground and can be a major source of Pb-210 to grazing animals. It is quite highly bioavailable to animals, with a fractional gastrointestinal absorption ~20 % and is accumulated mainly in calcified tissues. Aquatic biota exhibit concentration ratios relative to water of ~200 in both marine and freshwater fish, and ~1,000 in marine molluscs, crustaceans and seaweed.

Effects on organisms

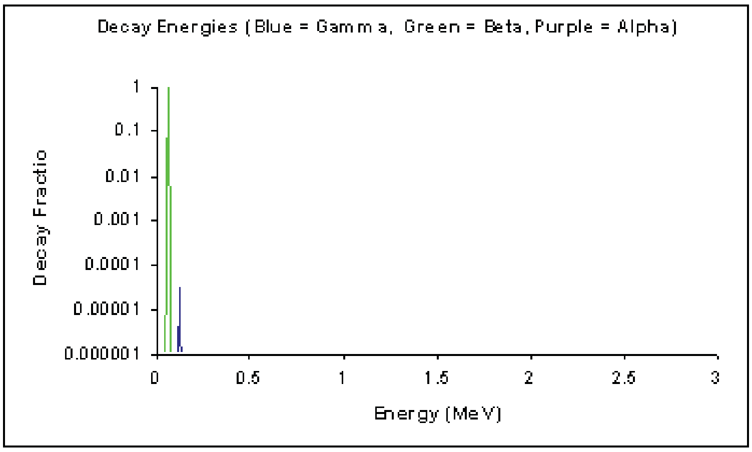
Dose effects/dosimetry	Species-specific considerations
Pb-210 emits low-energy beta particles together with a small amount of low energy photons. Its short-lived daughter, Bi-210, is a pure beta emitter.. However, this then decays to Po-210, which is an alpha emitter and is often a more important contributor to internal dose than is its ancestor Pb-210.	Naturally occurring Pb-210 is highly accumulated in marine organisms and in organisms such as reindeer that graze on plants with a high surface area per unit area of land such as lichens.

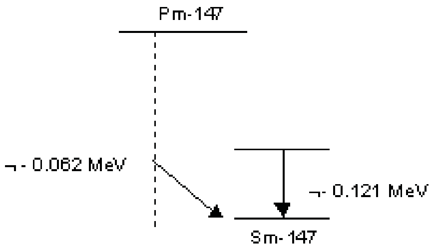
Name	Promethium-147	*Symbol*	Pm-147	*Origin*	Fission
Radioactive half-life	2.6 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Sm-147 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• As a beta source for thickness gauges • As a coating for self-luminous watch dials • Potentially as a heat source for space probes and satellites
Modes of release	Land	• Not generally released to land
	Air	• Not generally released to air
	Water	• Not generally released to water

Decay modes





Average beta energy = 0.062 MeV
Total gamma energy = 4.4 10^{-5} MeV

Chemical properties/characteristics

Speciation	Analogue species
Promethium is a rare earth element that shows an oxidation state of +3, and whose compounds are typical of other rare earth compounds. As such, promethium forms compounds with hydrogen, oxygen and the halides. It also forms stable complexes.	There are considerable similarities in the chemistry, biochemistry and biogeochemistry of all the lanthanide elements. In particular, Ce, Sm and Eu are moderately extensively studied elements that are analogous to Pm.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pm-147 is highly particle reactive, and hence would remain bound to soil particles and on the surfaces of plants. Transfers from plant to soil and bulk movement of soils would be the main transport mechanisms.	Pm-147 is highly particle reactive in the aquatic environment. It is likely to bind to suspended sediments close to its point of discharge and migrate lost from the water column by deposition of those sediments.	If Pm-147 was released to the atmosphere, it would be as an aerosol and probably in oxide form.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The high particle reactivity of Pm-147 mean that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, bottom sediments close to the source of release may form an important sink.	Pm-147 is not very bioavailable to animals. The fractional gastrointestinal absorption is typically <0.001. Any Pm-147 that is absorbed is mainly deposited in the liver and skeleton. Intake by terrestrial animals is likely to be mainly the ingestion of Pm-147 present on the exterior surfaces of plants or deposited on soil. Very little uptake from the gastrointestinal tract is anticipated, except perhaps in pre-weaned animals. In the aquatic environment uptake by fish and invertebrates is mainly direct from the water rather than food. Uptake by aquatic plants is likely to be by surface adsorption.

Effects on organisms

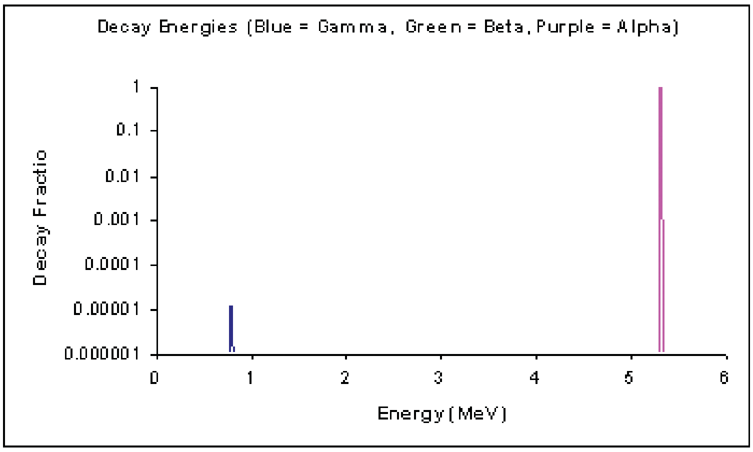
Dose effects/dosimetry	Species-specific considerations
Pm-147 is almost exclusively an emitter of low-energy beta particles. External deposits of Pm-147 on plants and animals will only result in irradiation of superficial outer tissues, which are often unsensitive to radiation exposure. Internal exposure will be limited by the low bioavailability of Pm-147.	The high uptakes in molluscs, crustaceans and aquatic plants could be important.

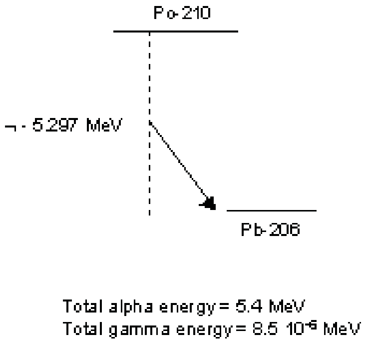
Name	Polonium-210	*Symbol*	Po-210	*Origin*	Radiogenic
Radioactive half-life	138 days	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Bi-210	*Daughter*	Pb-206	*Detection*	Laboratory

Production, uses and modes of release

Production		• Naturally in all environmental media from the decay of U-238 • By product of uranium mining and milling
Uses		• Source of electric power for space vehicles
Modes of release	Land	• Disposed uranium mill tailings
	Air	• From burning coal • During treatment of spent fuel
	Water	• During treatment of spent fuel

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Polonium is a Group VI element that forms compounds with the halogens, hydrogen, and oxygen to produce a range of oxides. All polonium compounds hydrolyse in water.	Po-210 is the daughter of Pb-210. Its environmental behaviour is strongly conditioned by that of its parent. As extensive environmental studies have been undertaken relating to Pb-210 and Po-210, it is not appropriate to rely on analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Po-210 is formed in the terrestrial environment from deposited Pb-210. Po-210 is highly particle reactive, so will tend to remain in situ rather than migrating in surface or groundwaters.	Po-210 is produced in aquatic systems from the decay of Pb-210. Owing to its particle reactivity, it will tend to bind to sediments.	Po-210 can be formed from Pb-210 in the atmosphere. However, as the mean residence time of dust suspended in the troposphere is only about 15 days, there is little time for its ingrowth in the atmosphere.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Pb-210 typically decays close to its site of production from Pb-210.	Po-210 is not very available to plants. The fractional gastrointestinal absorption of Po-210 in mammals is typically ~10 %. Po-210 entering the systemic circulation is widely distributed in soft tissues. Although it has no particular affinity for bone, it is often found there in higher concentrations than in other tissues, having been produced by decay of Pb-210. Concentrations of Po-210 in aquatic foods are typically similar to, or rather higher than, those of Pb-210. For fish products, UNSCEAR (2000) gives reference concentrations for Po-210 of 2 Bq/kg.

Effects on organisms

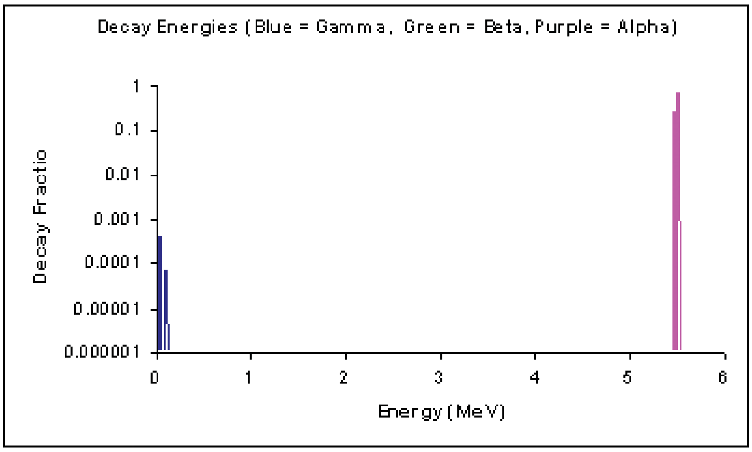
Dose effects/dosimetry	Species-specific considerations
Po-210 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Po-210 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

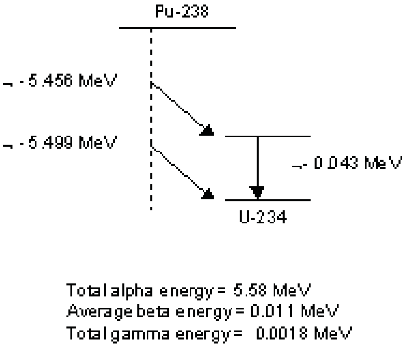
Name	Plutonium-238	*Symbol*	Pu-238	*Origin*	Breeding
Radioactive half-life	87.7 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Cm-242	*Daughter*	U-234 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Formed by neutron activation of uranium in a nuclear reactor, followed by decay of the activation products
Uses		• As a power source for satellites and other space equipment • As a power source for heart pacemakers
Modes of release	Land	• Deposition to soils as a result of weapons testing • Releases from nuclear reactors or experimental facilities
	Air	• Releases due to weapons testing • Releases from nuclear reactors or experimental facilities
	Water	• Releases from nuclear reactors or experimental facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
In aqueous solution, plutonium can exhibit any of four oxidation states. The stable oxidation state(s) in any solution are a function of environmental conditions such as pH and Eh. Plutonium reacts slowly with water and rapidly with dilute acids. It forms halide and oxide compounds.	There are chemical, biochemical and biogeochemical similarities between Pu and various other actinides, notably Np, Am and Cm. However, the environmental behaviour of Pu has been studied more extensively than those other actinides, so there is little merit in using them as analogues for Pu.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pu-238 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination.	Pu-238 is also highly particle reactive in the aquatic environment and therefore tends to bind to suspended sediments and hence migrate to bottom sediments.	Pu-238 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its high particle reactivity, Pu-238 will tend to remain in such soil systems until it decays. In aquatic systems, bottom sediments are the most likely environmental sink.	Pu-238 is strongly excluded from plants and is mainly present on their surfaces as external contamination. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation. Uptake from the gastrointestinal tract is limited (<0.1 %), although enhanced concentrations of Pu-238 may occur in the liver and skeleton. Concentrations in marine and freshwater fish are only about a factor 30 higher than concentrations in water. However, concentrations in molluscs, crustaceans and aquatic plants can be a factor of 300 or more higher than the surrounding water.

Effects on organisms

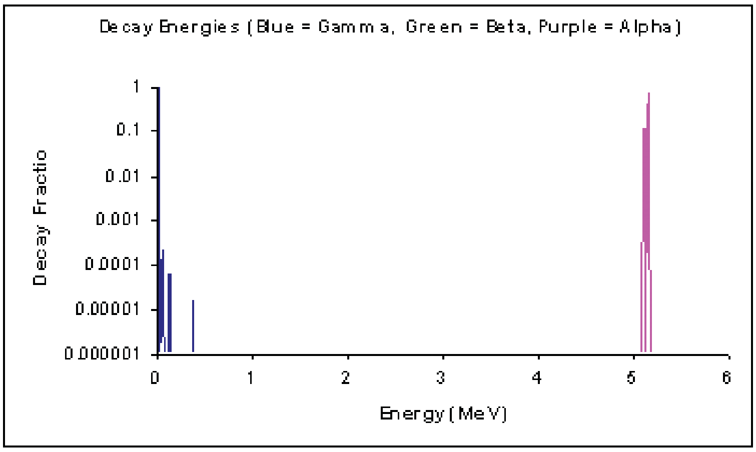
Dose effects/dosimetry	Species-specific considerations
Pu-238 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Pu-238 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

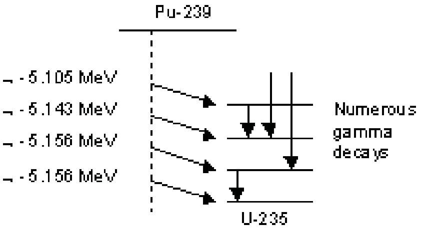
Name	Plutonium-239	*Symbol*	Pu-239	*Origin*	Breeding
Radioactive half-life	2.4 x 10^4 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Np-239	*Daughter*	U-235 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Formed by neutron activation of uranium in a nuclear reactor, followed by decay of the activation products
Uses		• As the basic fuel for fast breeder reactors • The source of explosive power in nuclear weapons
Modes of release	Land	• Deposition to soils as a result of weapons testing • Releases from nuclear reactors or experimental facilities
	Air	• Releases due to weapons testing • Releases from nuclear reactors or experimental facilities
	Water	• Liquid discharges from nuclear facilities

Decay modes





Total alpha energy = 5.23 MeV
Average beta energy = 0.0067 MeV
Total gamma energy = 0.0008 MeV

Chemical properties/characteristics

Speciation	Analogue species
In aqueous solution, plutonium can exhibit any of four oxidation states. The stable oxidation state(s) in any solution are a function of environmental conditions such as pH and Eh. Plutonium reacts slowly with water and rapidly with dilute acids. It forms halide and oxide compounds.	There are chemical, biochemical and biogeochemical similarities between Pu and various other actinides, notably Np, Am and Cm. However, the environmental behaviour of Pu has been studied more extensively than those other actinides, so there is little merit in using them as analogues for Pu.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pu-239 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination.	Pu-239 is also highly particle reactive in the aquatic environment and therefore tends to bind to suspended sediments and hence migrate to bottom sediments.	Pu-239 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its high particle reactivity, Pu-239 will tend to remain in such soil systems. In aquatic systems, bottom sediments are the most likely environmental sink.	Pu-239 is strongly excluded from plants and is mainly present on their surfaces as external contamination. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation. Uptake from the gastrointestinal tract is limited (<0.1 %), although enhanced concentrations of Pu-239 may occur in the liver and skeleton. Concentrations in marine and freshwater fish are only about a factor 30 higher than concentrations in water. However, concentrations in molluscs, crustaceans and aquatic plants can be a factor of 300 or more higher than the surrounding water.

Effects on organisms

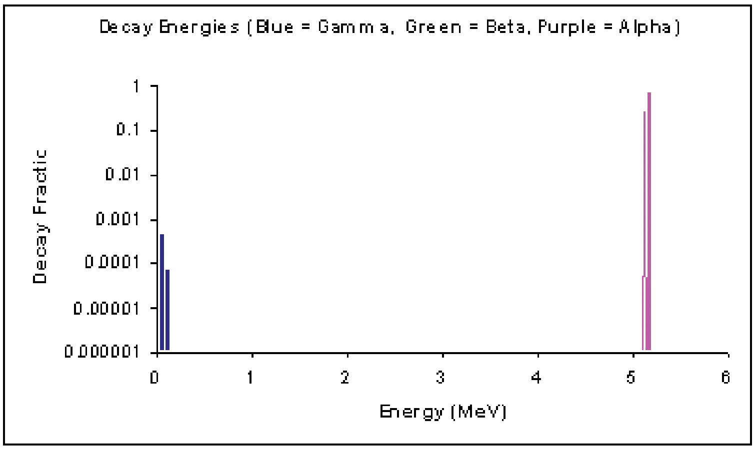
Dose effects/dosimetry	Species-specific considerations
Pu-239 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Pu-239 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

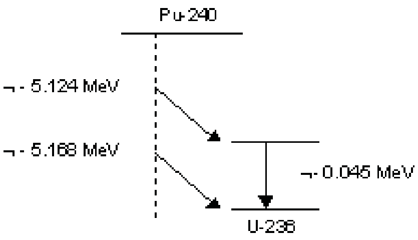
Name	Plutonium-240	*Symbol*	Pu-240	*Origin*	Breeding
Radioactive half-life	6,537 years	*Principal decay mode*	Alpha	*Grouping*	Artificial
Parent	Cm-244	*Daughter*	U-236 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Formed by neutron activation of uranium in a nuclear reactor, followed by decay of the activation products
Uses		• No significant commercial uses
Modes of release	Land	• Deposition to soils as a result of weapons testing • Releases from nuclear reactors or experimental facilities
	Air	• Releases due to weapons testing • Releases from nuclear reactors or experimental facilities
	Water	• Releases from nuclear reactors or experimental facilities

Decay modes
Chemical properties/characteristics





Total alpha energy = 5.24 MeV
Average beta energy = 0.011 MeV
Total gamma energy = 0.0017 MeV

Speciation	Analogue species
In aqueous solution, plutonium can exhibit any of four oxidation states. The stable oxidation state(s) in any solution are a function of environmental conditions such as pH and Eh. Plutonium reacts slowly with water and rapidly with dilute acids. It forms halide and oxide compounds.	There are chemical, biochemical and biogeochemical similarities between Pu and various other actinides, notably Np, Am and Cm. However, the environmental behaviour of Pu has been studied more extensively than those other actinides, so there is little merit in using them as analogues for Pu.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pu-240 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination.	Pu-240 is also highly particle reactive in the aquatic environment and therefore tends to bind to suspended sediments and hence migrate to bottom sediments.	Pu-240 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its high particle reactivity, Pu-240 will tend to remain in such soil systems until it decays. In aquatic systems, bottom sediments are the most likely environmental sink.	Pu-240 is strongly excluded from plants and is mainly present on their surfaces as external contamination. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation. Uptake from the gastrointestinal tract is limited (<0.1 %), although enhanced concentrations of Pu-240 may occur in the liver and skeleton. Concentrations in marine and freshwater fish are only about a factor 30 higher than concentrations in water. However, concentrations in molluscs, crustaceans and aquatic plants can be a factor of 300 or more higher than the surrounding water.

Effects on organisms

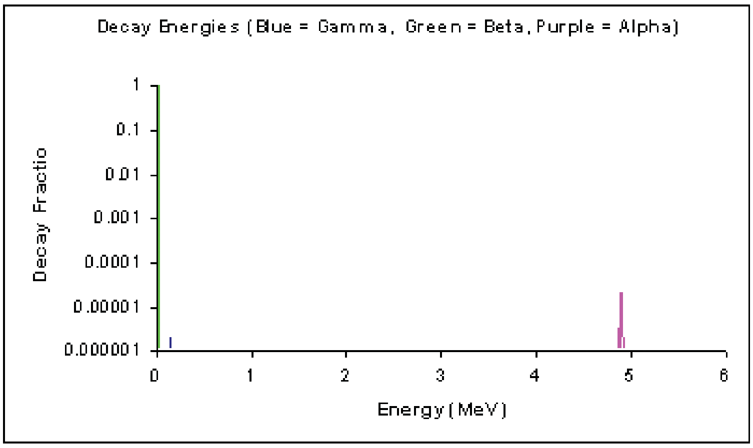
Dose effects/dosimetry	Species-specific considerations
Pu-240 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Pu-240 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

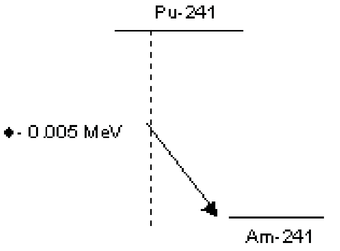
Name	Plutonium-241	*Symbol*	Pu-241	*Origin*	Breeding
Radioactive half-life	14.4 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	Cm-245	*Daughter*	Am-241 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Formed by neutron activation of uranium in a nuclear reactor, followed by decay of the activation products
Uses		• No significant commercial uses
Modes of release	Land	• Deposition to soils as a result of weapons testing • Releases from nuclear reactors or experimental facilities
	Air	• Releases due to weapons testing • Releases from nuclear reactors or experimental facilities
	Water	• Liquid discharges from nuclear facilities

Decay modes
Chemical properties/characteristics





Total alpha energy = 0.0001 MeV
Average beta energy = 0.005 MeV
Total gamma energy = $2.5\ 10^{-6}$ MeV

Speciation	Analogue species
In aqueous solution, plutonium can exhibit any of four oxidation states. The stable oxidation state(s) in any solution are a function of environmental conditions such as pH and Eh. Plutonium reacts slowly with water and rapidly with dilute acids. It forms halide and oxide compounds.	There are chemical, biochemical and biogeochemical similarities between Pu and various other actinides, notably Np, Am and Cm. However, the environmental behaviour of Pu has been studied more extensively than those other actinides, so there is little merit in using them as analogues for Pu.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Pu-241 is highly particle reactive and therefore binds strongly to soils and sediments. It is strongly excluded from plants and is mainly present on their surfaces as external contamination.	Pu-241 is also highly particle reactive in the aquatic environment and therefore tends to bind to suspended sediments and hence migrate to bottom sediments.	Pu-241 would be expected to disperse as an aerosol. The most likely chemical form would be an oxide, but other forms, e.g. nitrate, might also arise.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its high particle reactivity, Pu-241 will tend to remain in such soil systems until it decays. In aquatic systems, bottom sediments are the most likely environmental sink.	Pu-241 is strongly excluded from plants and is mainly present on their surfaces as external contamination. The main routes of intake by animals will typically be by ingestion of contaminated soil or sediment, or by inhalation. Uptake from the gastrointestinal tract is limited (<0.1 %), although enhanced concentrations of Pu-241 may occur in the liver and skeleton. Concentrations in marine and freshwater fish are only about a factor 30 higher than concentrations in water. However, concentrations in molluscs, crustaceans and aquatic plants can be a factor of 300 or more higher than the surrounding water.

Effects on organisms

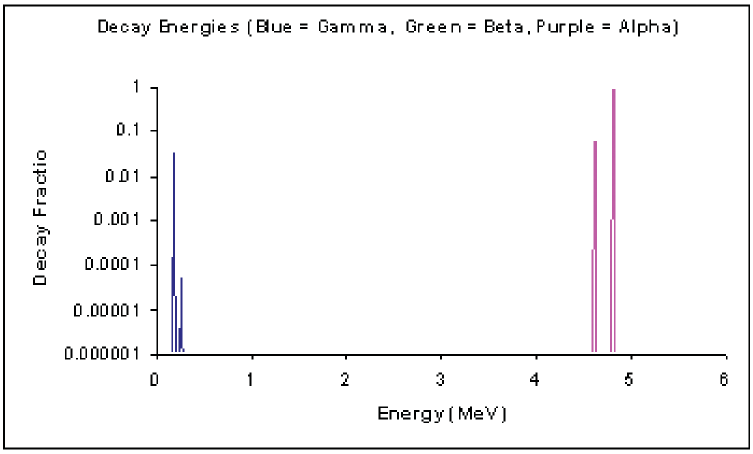
Dose effects/dosimetry	Species-specific considerations
Pu-241 is primarily an emitter of very low energy beta particles. Therefore, Pu-241 is of greatest potential significance when internally incorporated. Internally incorporated Pu-241 may be less important dosimetrically than its decay product Am-241 because of the intense alpha emissions of the latter.	No species-specific considerations

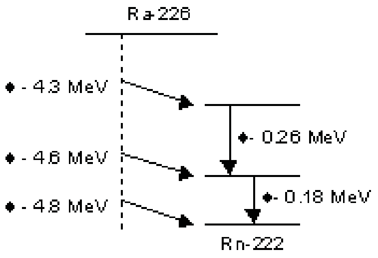
Name	Radium-226	*Symbol*	Ra-226	*Origin*	Radiogenic
Radioactive half-life	1,600 years	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Th-230	*Daughter*	Rn-222 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Naturally in all environmental media through the decay of U-238 • By product of uranium mining and milling
Uses		• In sealed sources for the treatment of cancer • Historically, used as a component of luminous paint and in lightening conductors
Modes of release	Land	• Disposed uranium mill tailings • Disposal of luminising waste (past practices)
	Air	• From burning coal • As part of spent fuel
	Water	• As part of spent fuel

Decay modes





Total alpha energy = 4.86 MeV
Total gamma energy = 0.0067 MeV

Chemical properties/characteristics

Speciation	Analogue species
Radium is an alkaline earth element and, as a consequence, the most important species is the Ra^{2+} ion. Isotopes of radium can therefore be expected to take part in a number of precipitation and substitution reactions. Precipitation as sulphate, carbonate or hydroxide is possible.	The alkaline earth elements Ca, Sr, Ba and Ra exhibit close chemical, biochemical and biogeochemical analogies. However, Ra has been studied extensively in its own right, so it is not necessary to rely on analogies with the other alkaline earths.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ra-226 is widely dispersed in soils due to the presence of U-238. It mainly decays in situ, as it is incorporated in the mineral phase. Ra-226 is strongly excluded from plants.	The Ra-226 content of surface waters is low and it has only a limited tendency to bind with sediments. However, highly insoluble Ba/Ra sulphates may be precipitated in the context of uranium processing.	Ra-226 is not generally of great interest in the context of atmospheric releases, although it could be dispersed from facilities where uranium ores have been processed.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Most Ra-226 decays local to its point of production from decay of primordial U-238. However, Ra-226 entering surface waters may either decay in the water column or be transferred to sediments. High concentrations of Ra-226 may accumulate in tailings ponds at uranium ore processing facilities.	Ra-226 is strongly excluded from plants. Its fractional gastrointestinal absorption in mammals is typically only ~3 %. Ra-226 entering the systemic circulation is mainly accumulated in mineral bone. Ra-226 exhibits concentration ratios relative to water of about 50 in both marine and freshwater fish. It accumulates in the bone, scales and fins. Concentration ratios in marine invertebrates range from 3 to 7,000. Typical values are 100 for molluscs and 1,000 for crustaceans.

Effects on organisms

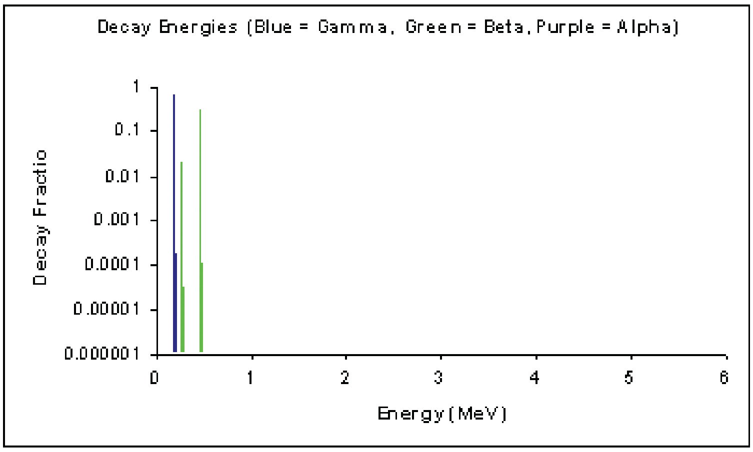
Dose effects/dosimetry	Species-specific considerations
Ra-226 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Thus, Ra-226 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation. Ra-226 decays to Rn-222. Although much of this Rn-222 diffuses out of the body, some remains trapped and decays in situ.	No species-specific considerations

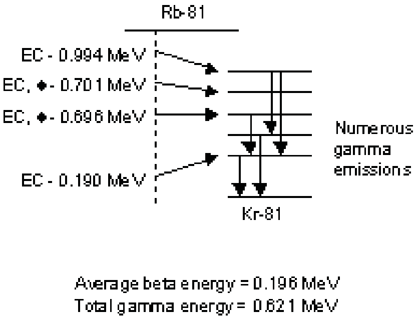
Name	Rubidium-81	*Symbol*	Rb-81	*Origin*	Fission
Radioactive half-life	4.6 hours	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Kr-81 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• By irradiation of stable precursors in a cyclotron or nuclear reactor
Uses		• In the production of krypton-81 (the decay product)
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air
	Water	• Hospital releases to sewers, but would probably decay away before this can occur

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Rubidium is an alkali metal whose chemical behaviour is determined by the properties of the Rb^+ ion. Most of the compounds of rubidium are ionic in nature, although more complex species can be formed.	Rb has no known biological role, but it is a close chemical analogue for K and can substitute for it, to some degree, in biota. In terms of binding to soils and sediments, both K and Cs are useful analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Rubidium is moderately particle reactive and so a substantial proportion will remain in situ. A limited amount will be transported around the terrestrial environment in surface and groundwaters.	Freshwater sediments may absorb Rb-81 significantly. But is likely to behave conservatively in the marine environment.	It is likely to be released as an aerosol, but its very short half-life will limit the amount of deposition to plants and ground surfaces

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its short half-life Rb-81 in the terrestrial environment will decay close to its point of deposition. In aquatic environments, Rb-81 will mainly decay in the water column as it disperses, or possibly in deposited freshwater sediments.	The very short radioactive half-life of Rb-81 will preclude substantial uptake by plants. Rb-81 is highly bioavailable to animals and would be efficiently absorbed by animals grazing on externally contaminated vegetation. It would rapidly become relatively uniformly distributed throughout the bodies of those animals. Concentration ratios relative to water are likely to be much higher in freshwater than marine organisms, although the very short half-life of Rb-81 would limit the extent of accumulation.

Effects on organisms

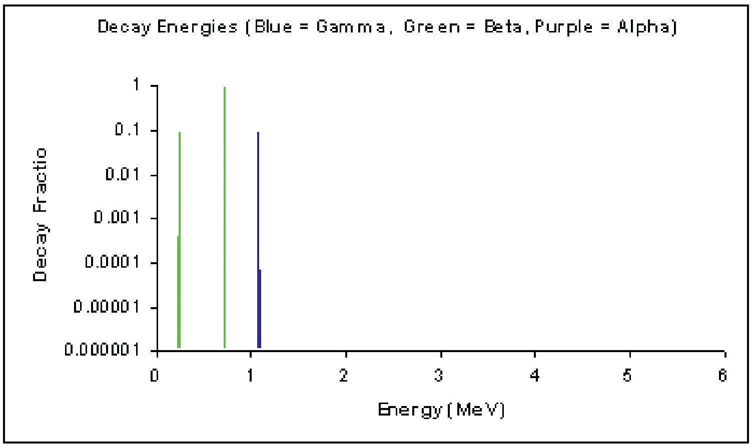
Dose effects/dosimetry	Species-specific considerations
Rb-81 is a positron emitter. Therefore, there is a strong 0.511 MeV gamma ray emission. External exposure will therefore be an important exposure pathway. Rb-81 taken up by biota would be relatively uniformly distributed throughout their tissues, so individual organ and tissue doses would be of similar magnitude to the average whole-body dose.	As Rb-81 is a chemical analogue for K, which is an essential element for almost all biota, there are no major species-specific considerations.

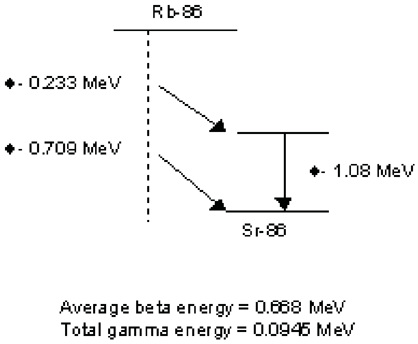
Name	Rubidium-86	*Symbol*	Rb-86	*Origin*	Fission
Radioactive half-life	18.7 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Sr-86	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• In medicine for the determination and treatment of electrolyte disorders
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Rubidium is an alkali metal whose chemical behaviour is determined by the properties of the Rb^+ ion. Most of the compounds of rubidium are ionic in nature, although more complex species can be formed.	Rb has no known biological role, but it is a close chemical analogue for K and can substitute for it, to some degree, in biota. In terms of binding to soils and sediments, both K and Cs are useful analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Rubidium is moderately particle reactive and so a substantial proportion will remain in situ. A limited amount will be transported around the terrestrial environment in surface and groundwaters.	Freshwater sediments may absorb Rb-86 significantly. But is likely to behave conservatively in the marine environment.	Rb-86 is likely to be released as an aerosol and may be deposited on plants and soils by wet and dry deposition processes.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its short half-life, Rb-86 in the terrestrial environment will decay close to its point of deposition. In aquatic environments, Rb-86 will mainly decay in the water column as it disperses, or possibly in deposited freshwater sediments.	Significant rapid, metabolically active foliar absorption of Rb-86 deposited on plants is likely to occur. Rb-86 is highly bioavailable to animals and would be efficiently absorbed by animals grazing on externally contaminated vegetation. It would rapidly become relatively uniformly distributed throughout the bodies of those animals. Concentration ratios relative to water are likely to be much higher in freshwater than marine organisms. For freshwater organisms, values of a few hundred are typical.

Effects on organisms

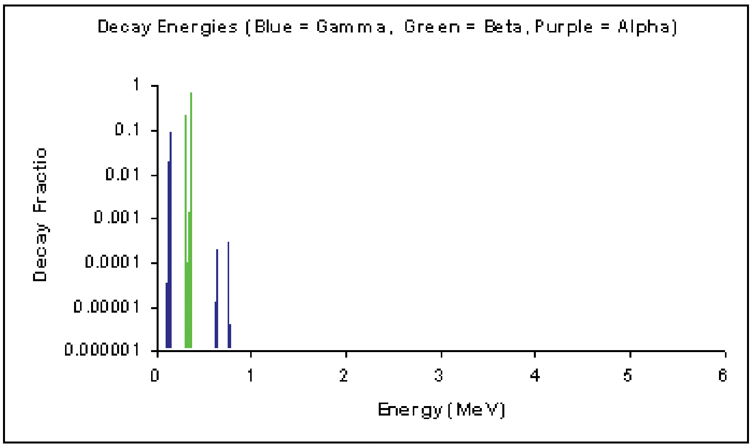
Dose effects/dosimetry	Species-specific considerations
Rb-86 taken up by biota would be relatively uniformly distributed throughout their tissues, so individual organ and tissue doses would be of similar magnitude to the average whole-body dose.	As Rb-86 is a chemical analogue for K, which is an essential element for almost all biota, there are no major species-specific considerations.

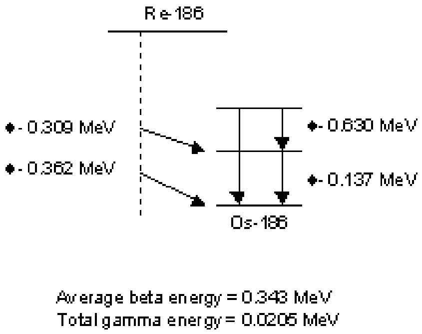
Name	Rhenium-186	*Symbol*	Re-186	*Origin*	Activation
Radioactive half-life	3.7 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Os-186 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced by irradiation of stable precursors in a cyclotron or nuclear reactor
Uses		• To provide pain relief from bone cancer • In the treatment of rheumatoid arthritis
Modes of release	Land	• Sewage sludge application to land, but would probably decay substantially before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





R

Chemical properties/characteristics

Speciation	Analogue species
Rhenium is a Group VII element that can show oxidation states from -1 through to +7. It forms compounds with the halogens and oxygen, and can form an extensive range of complexes, of which many contain bonds with oxygen or nitrogen.	Almost nothing is known about the environmental behaviour of Re. Although there are chemical similarities with Tc, both elements have complex, redox-dependent chemistries and it would not be appropriate to rely on Tc as an environmental analogue for Re.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Re-186 is most likely to enter the terrestrial environment by atmospheric deposition. It is likely to exhibit only limited particle reactivity in oxic conditions.	As for the terrestrial environment, Re-186 is likely to exhibit only limited particle reactivity in oxic conditions.	If Re-186 were released to the atmosphere, it would disperse as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In the terrestrial environment, Re-186 is likely to decay close to its site of deposition. In the aquatic environment, it is likely to decay as it disperses in the water column.	Foliar uptake of Re-186 could occur, but its short half-life means that it will mainly be present on the external surfaces of plants. Re-186 ingested by animals is likely to be highly bioavailable and widely dispersed throughout soft tissues. Re-186 may exhibit high concentration ratios relative to water in marine invertebrates and seaweed. However, its short half-life may prevent such ratios being achieved.

Effects on organisms

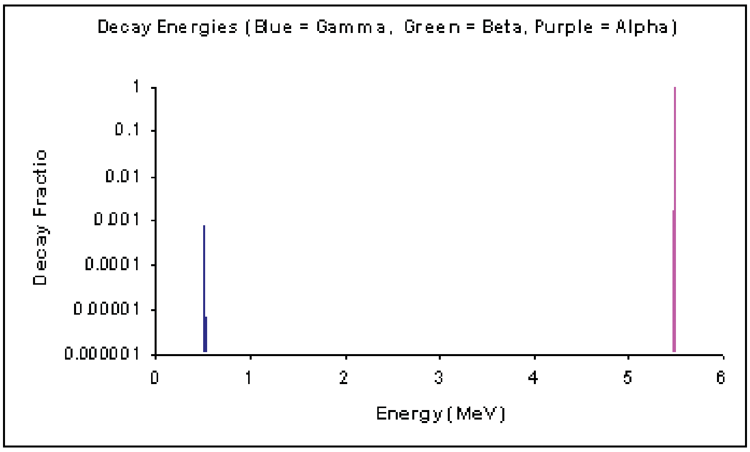
Dose effects/dosimetry	Species-specific considerations
Re-186 is mainly a beta emitter. However, a small amount of gamma emission also occurs. Because of its potentially high bioavailability, the pathway of greatest interest may possibly be internal exposure of animals.	Insufficient information is available to permit any comment to be made.

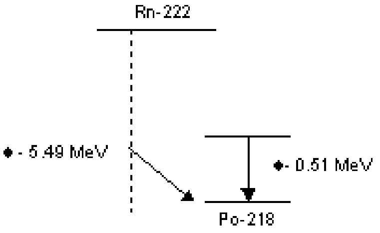
Name	Radon-222	*Symbol*	Rn-222	*Origin*	Radiogenic
Radioactive half-life	3.8 days	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Ra-226	*Daughter*	Po-218 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of radium-226 in the uranium-238 decay chain
Uses		• Sometimes used in sealed tubes in the treatment of cancer
Modes of release	Land	• Naturally present in soil and rock pores containing uranium
	Air	• Emitted from soils and rocks containing uranium
	Water	• Naturally present in waters containing radioactive precursors

Decay modes





Total alpha energy = 5.59 MeV
Total gamma energy = $3.98\ 10^{-4}$ MeV

Chemical properties/characteristics

Speciation	Analogue species
Radon is a noble gas and, as such, forms only a limited number of chemical compounds due to its lack of reactivity. One such example is RnF_2.	There are broad similarities in the behaviour of all the noble gases (Ne, Ar, Kr, Xe, Rn). However, Rn-222 is characterised by various short-lived, chemically reactive and radioactive progeny. As it has been studied extensively in its own right, there is no need to resort to analogies.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Rn-222 is not deposited to a significant degree in terrestrial environments. Its short-lived descendants do deposit to surfaces, but this is mainly relevant in mitigating inhalation exposures (doses from Rn-222 inhalation are dominated by the decay of short-lived descendants).	Rn-222 is produced from Ra-226 in aquatic environments, but is of little radiological significance compared with its long-lived descendants, Pb-210 and Po-210.	Rn-222 is produced from Ra-226 present in soils and sediments and is subsequently released to the atmosphere. Outdoor concentrations vary by about a factor of 100, depending on the geographical context and near-surface uranium concentrations. Concentrations are higher in enclosed spaces, e.g. burrows.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Rn-222 released from soils and sediments decays mainly in the atmosphere. However, much of the Rn-222 produced in soils and sediments decays in situ. Rn-222 produced at depths of more than about 0.3 m has little chance of escaping from the soil surface.	The main intake route for Rn-222 and its short-lived progeny is inhalation. Being a noble gas, very little radon is retained in the body. However, short-lived descendants can settle and attach themselves to the lung surface.

Effects on organisms

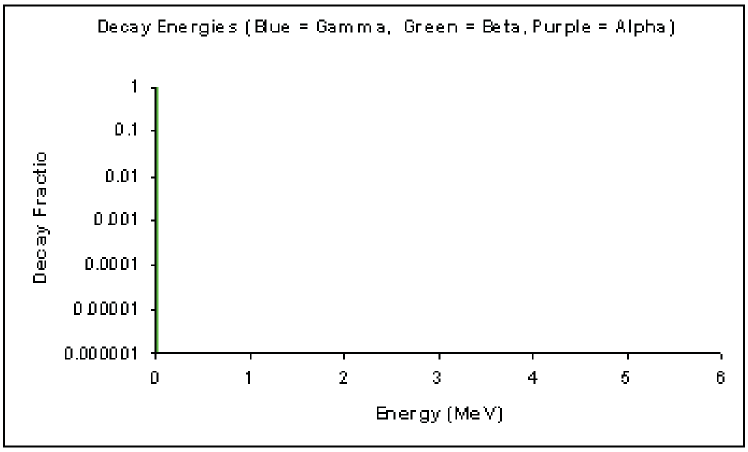
Dose effects/dosimetry	Species-specific considerations
Rn-222 and its short-lived progeny emit a mixture of alpha, beta and gamma radiation. In animals, short-lived progeny of Rn-222 deposit on, and preferentially irradiate, the surfaces of the trachea and bronchi.	Rn-222 is mainly of interest in respect of terrestrial animals. Exposures of burrow-dwelling animals are of particular importance.

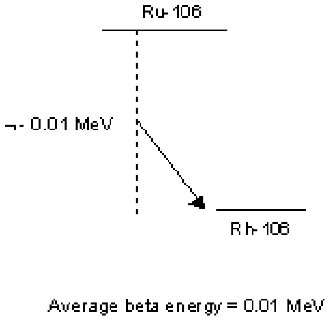
Name	Ruthenium-106	*Symbol*	Ru-106	*Origin*	Fission
Radioactive half-life	373.6 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Rh-106 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced as a result of fission processes in a nuclear reactor
Uses		• Sometimes used in medical research and diagnostics
Modes of release	Land	• Reaches surface soils as a result of sewage sludge applied to land
	Air	• Sometimes released from nuclear reactors, hospitals and research facilities
	Water	• Sometimes released from nuclear reactors, hospitals and research facilities • Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Ruthenium is a platinum metal that shows oxidation states from -2 through to +8; the principal ones are +2 and +3. Ruthenium forms compounds with the halogens and oxygen. It can also form various complexes, of which those involving bonding to nitrogen are the most stable.	There are broad similarities in the behaviour of all the noble gases (Ne, Ar, Kr, Xe, Rn). However, Rn-222 is characterised by various short-lived, chemically reactive and radioactive progeny. As it has been studied extensively in its own right, there is no need to resort to analogies.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Ru-106 is moderately adsorbed in mineral soils, but is strongly adsorbed in organic soils. In mineral soils, cationic forms adsorb much more strongly than anionic forms. Nitrogen-ruthenium complexes are only poorly adsorbed and are available for plant uptake.	Ru-106 is highly particle reactive, although the degree of sorption to freshwater sediments is much less than to marine sediments. In seawater, almost no Ru is present in ionic form. Particulate-bound and colloidal Ru are dominant.	If Ru-106 were to be released to atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Intake and uptake routes In terrestrial environments, Ru-106 can be expected to decay close to its site of deposition. In freshwater environments, it may be transported as ionic or colloidal forms. In the marine environment, decay will occur in the water column or deposited sediments.	In terrestrial environments, uptake to plants from foliar absorption is likely to be more important than root uptake in the first season after deposition. The fractional gastrointestinal absorption of Ru in mammals is <10 %. Ru-106 entering the systemic circulation becomes relatively uniformly distributed and is well retained. Concentration ratios relative to water are <10 for the soft tissues of crustaceans, but ~100 for whole animals. For molluscs, soft tissue and whole body ratios are 500 and 2,000, respectively. In fish, whole body ratios are typically between 10 to 100.

Effects on organisms

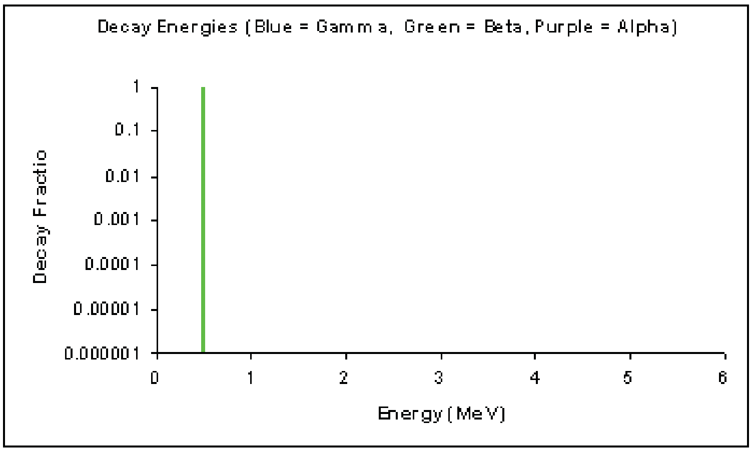
Dose effects/dosimetry	Species-specific considerations
Ru-106 is a soft beta emitter. However, it decays to the very short-lived Rh-106, which emits energetic beta particles and moderately energetic gamma rays. Internal and external exposures from Ru-106/Rh-106 should be taken into account.	Molluscs and crustaceans accumulate Ru-106 in their guts and external organs. Uptake to the shell can be particularly important.

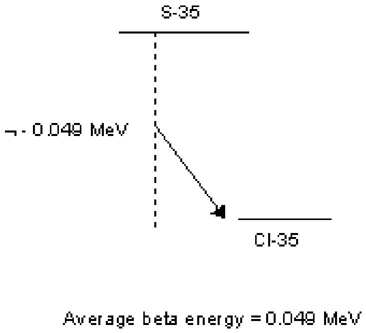
Name	Sulphur-35	*Symbol*	S-35	*Origin*	Activation
Radioactive half-life	87.3 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	P-35	*Daughter*	Cl-35	*Detection*	Laboratory

Production, uses and modes of release

Production		• By irradiation of stable isotopes of sulphur and carbon with neutrons in a nuclear reactor or cyclotron
Uses		• Used in research as a radiotracer
Modes of release	Land	• Deposition from air onto surface soils
	Air	• Released from gas-cooled nuclear reactors
	Water	• Release to sewers • Leaching to groundwater from surface soils

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Sulphur can exhibit oxidation states of -2, 0, +2, +4 and +6. It can thus form a wide range of compounds, particularly with the halogens. Sulphur also has a great tendency towards catenation (the formation of element-element bonds).	Sulphur is an essential element for all living organisms. There are extensive studies of its behaviour in the environment and it is inappropriate to consider it by analogy with any other element.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
S-35 is likely to enter the terrestrial environment by deposition from the atmosphere. S-35 as SO_2 is strongly taken up by plants through foliar absorption and is reduced to organic sulphur compounds. The mechanism of deposition and uptake is affected by seasonal factors.	The majority of sulphur in seawater is present as sulphate and little is thought to be present as particulates. Concentrations of sulphur in freshwaters are generally much lower than those in marine waters.	S-35 is likely to be released to the atmosphere as the gases COS or SO_2. However, it could also be released as a particulate aerosol, e.g. sulphate.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
S-35 is mainly of interest in the terrestrial environment. It will mainly be accumulated by plants and soils and will decay in situ.	S-35 will be rapidly and efficiently taken up in plants by foliar absorption. It is highly available to animals, gastrointestinal absorption being virtually complete. S-35 entering the systemic circulation from diet is uniformly distributed in the body and is well retained. Concentration ratios in aquatic organisms relative to water are ~0.5 and 100 for marine and freshwater organisms, respectively.

Effects on organisms

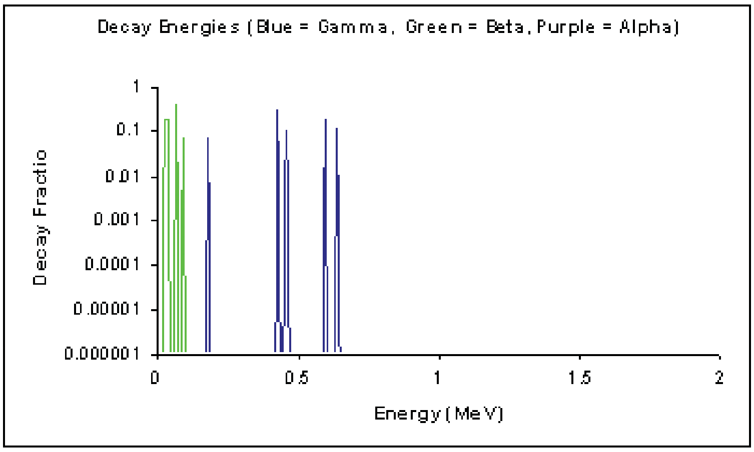
Dose effects/dosimetry	Species-specific considerations
S-35 is a pure beta emitter and is only of interest in the context of internal irradiation. As it is relatively uniformly distributed in plants and animals, doses to individual organs and tissues will be of similar magnitude to average whole-body doses.	No major species-specific considerations have been identified.

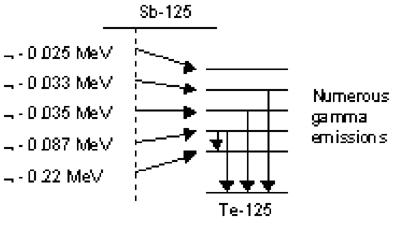
Name	Antimony-125	*Symbol*	Sb-125	*Origin*	Fission
Radioactive half-life	2.8 years	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Te-125m [R], Te-125	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• No significant uses outside research activities
Modes of release	Land	• During treatment and disposal of spent fuel
	Air	• During treatment and disposal of spent fuel
	Water	• Not generally released to water

Decay modes





Average beta energy = 0.099 MeV
Total gamma energy = 0.43 MeV

Chemical properties/characteristics

Speciation	Analogue species
Antimony is a metalloid of Group V, whose chemistry is dominated by the +3 and +5 oxidation states. Antimony forms compounds with hydrogen, oxygen, sulphur, halides and other elements. It can form antimonyl compounds involving antimony and oxygen $(SbO)^+$.	Sb exhibits some chemical and biochemical similarities to arsenic. However, there are also considerable differences and the environmental behaviour of Sb is best treated without reference to potential analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
In general, when Sb-125 is added to soils in soluble form, it can be expected to remain mobile as it is, at most, moderately particle reactive. Sb-125 is not very available to plants.	Sb-125 is likely to be present in both fresh and marine waters mainly in ionic form. However, a substantial fraction may become bound to suspended and bottom sediments.	If Sb-125 were released to the atmosphere, it would probably be as an aerosol rather than the highly toxic gas stibine (SbH3).

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In the terrestrial environment, some migration of Sb-125 in the soil profile can be expected before it decays. In aquatic environments, decay will occur mainly in the water column and only to a limited degree in deposited sediments.	Sb-125 is not very available to plants and there is no evidence of substantial foliar uptake. The fractional gastrointestinal absorption in mammals is typically ~1 %. Antimony is widely distributed in the soft tissues of mammals, but bone is the main long-term reservoir. Concentration ratios of Sb-125 in aquatic organisms relative to water are typically in the range 5 to 100.

Effects on organisms

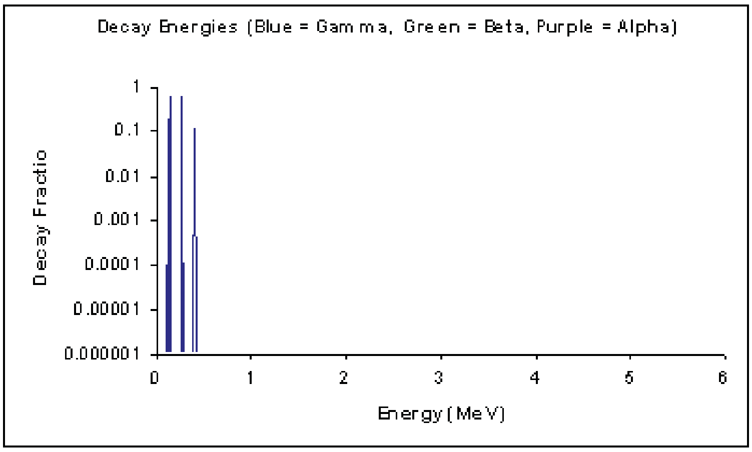
Dose effects/dosimetry	Species-specific considerations
Sb-125 is a mixed beta-gamma emitter. Gamma emissions are of high yield and moderate energy. Because of the low bioavailability of Sb-125, external irradiation may be more important than internal irradiation in terrestrial environments.	No major species-specific considerations have been identified.

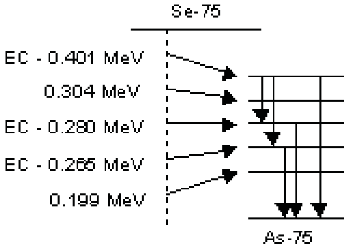
Name	Selenium-75	*Symbol*	Se-75	*Origin*	Activation
Radioactive half-life	120 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	As-75	*Detection*	In situ

Production, uses and modes of release

Production		• Neutron activation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• In medicine for diagnostic imaging • To investigate the production of digestive enzymes
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air, but some releases of volatile selenium compounds may occur from sewage sludge
	Water	• Hospital releases to sewers

Decay modes





Average beta energy = 0.014 MeV
Total gamma energy = 0.394 MeV

Chemical properties/characteristics

Speciation	Analogue species
Selenium can exist in one of four oxidation states: -2 (selenide compounds), 0 (elemental selenium), +4 (selenite compounds) and +6 (selenate compounds). Selenide and elemental selenium are expected to be present in reducing conditions, with selenite and selenate species appearing as conditions move towards oxidising.	There are considerable similarities between the chemistry and biochemistry of Se and S, and Se can substitute for S in a number of contexts. However, Se is an essential trace element in its own right, so this analogy should be used cautiously.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
The chemistry of Se in soils is complex, but it can bind strongly to clay minerals. The proportion of available Se in soils can vary from <1 % to 30 %. There are strong distinctions between normal and Se-deficient soils. Selenate is likely to be much more available than selenite.	Se-75 in aquatic systems is moderately particle reactive. Binding to sediments depends on the acidity and the Fe, Mn and clay contents of the sediments.	Se-75 could be released to atmosphere either as an aerosol or as a gas, e.g. dimethyl selenide.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Se-75 deposited in the terrestrial environment is likely to be strongly retained in the plant-soil system and decay close to its point of deposition. In aquatic systems, it may decay either in the water column or in bottom sediments, depending on the chemical form.	Se-75 is very highly bioavailable to both terrestrial plants and animals (especially as selenate) and is likely to be substantially accumulated, particularly in Se-deficient conditions. Both foliar uptake and root absorption are likely to be important in plants. Se is widely distributed in animal tissues and is well retained. Concentration ratios relative to water are ~100 for most aquatic organisms.

Effects on organisms

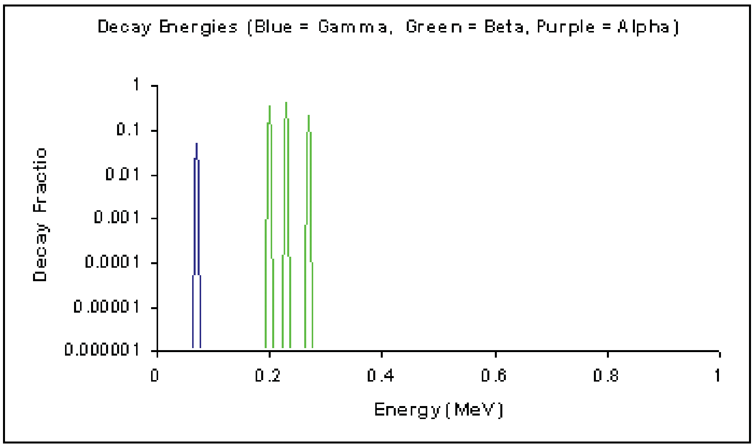
Dose effects/dosimetry	Species-specific considerations
Se-75 is predominantly a gamma-emitting radionuclide. However, because of its high bioavailability and relatively long half-life, internal irradiation is likely to be more important than external irradiation, especially for small organisms.	No major species-specific considerations have been identified. However, Se-deficient terrestrial environments are likely to be associated with an exceptionally high degree of bioavailability of Se-75.

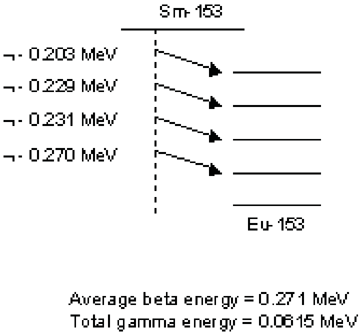
Name	Samarium-153	*Symbol*	Sm-153	*Origin*	Activation
Radioactive half-life	46.7 hours	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Eu-153	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor • By irradiating stable precursors in a cyclotron
Uses		• In medicine for relieving pain from secondary bone cancers • For diagnostic imaging and radioimmunotherapy
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Samarium is a rare earth element that shows oxidation states of +2 and +3, and whose compounds are typical of other rare earth compounds. As such, samarium forms compounds with hydrogen, oxygen and the halides. It also forms stable complexes.	There are considerable similarities in the chemistry, biochemistry and biogeochemistry of all the lanthanide elements. In particular, Ce and Eu are moderately extensively studied elements that are analogous to Sm.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Sm-153 is highly particle reactive, and hence would remain bound to soil particles and on the surfaces of plants. Transfers from plant to soil and bulk movement of soils would be the main transport mechanisms.	Sm-153 is highly particle reactive in the aquatic environment. It is likely to bind to suspended sediments close to its point of discharge, and deposit from the water column to bottom sediments.	If Sm-153 was released to the atmosphere, it would be as an aerosol and probably in oxide form.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The short half-life and high particle reactivity of Sm-153 mean that it is likely to decay close to its site of deposition in terrestrial environments. In aquatic environments, bottom sediments close to the source of release may form an important sink.	Intake by terrestrial animals is likely to be mainly the ingestion of Sm-153 present on the exterior surfaces of plants or deposited on soil. Sm-153 is not very bioavailable to animals. The fractional gastrointestinal absorption is typically <0.1 %. Any Sm-153 that is absorbed is mainly deposited in the liver and skeleton. In the aquatic environment, uptake by fish and invertebrates is mainly direct from the water rather than food. Uptake by aquatic plants is likely to be by surface adsorption.

Effects on organisms

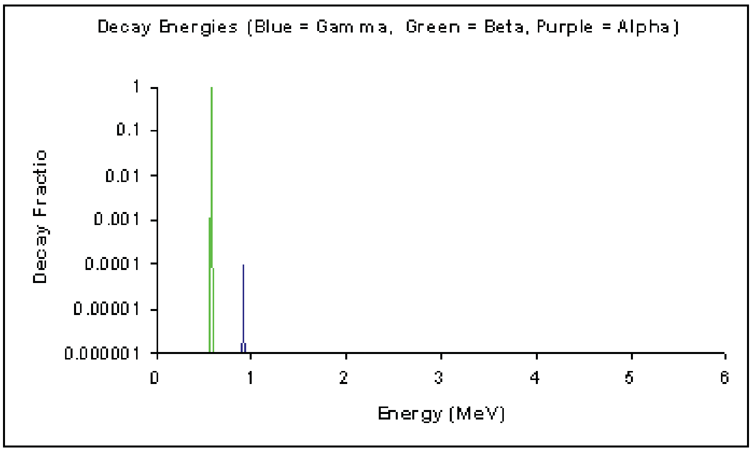
Dose effects/dosimetry	Species-specific considerations
Sm-153 is mainly an emitter of low-energy beta particles. External deposits of Sm-153 on plants and animals will mainly result in irradiation of superficial outer tissues, which are often insensitive to radiation exposure. Internal exposure will be limited by the low bioavailability of Sm-153.	The high uptakes in molluscs, crustaceans and aquatic plants could be important.

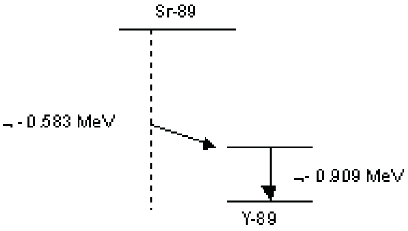
Name	Strontium-89	*Symbol*	Sr-89	*Origin*	Fission
Radioactive half-life	50.5 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Y-89	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced as a fission product in a nuclear reactor • In a cyclotron for medical purposes
Uses		• Used in medicine to treat metastases in bone cancer
Modes of release	Land	• Sewage sludge application to land
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Average beta energy = 0.583 MeV
Total gamma energy = $8.5\ 10^{-5}$ MeV

Chemical properties/characteristics

Speciation	Analogue species
Strontium is an alkaline earth element and thus the most important species is the Sr^{2+} ion. Isotopes of strontium can therefore be expected to take part in a number of precipitation and substitution reactions. Precipitation as sulphate, carbonate or hydroxide is possible.	The alkaline earths Ca, Sr, Ba and Ra exhibit considerable chemical, biochemical and biogeochemical similarities. Ratios of Sr-90 to stable Ca have often been used to characterise the environmental behaviour of the radionuclide.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Sr-89 is only weakly to moderately particle reactive in soils. However, its degree of mobility is limited by its short half-life. Foliar uptake of Sr-89 uptake can be significant.	Sr-89 has only a limited tendency to bind to sediments in either freshwater or marine systems.	Sr-89 would be expected to disperse as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Although Sr-89 is relatively mobile, its short half-life means it will largely decay in situ in terrestrial environments. However, in freshwater and marine environments, it may be widely dispersed before decaying, largely in the water column.	Sr-89 is moderately bioavailable to plants. Foliar uptake can be significant. Strontium is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~20 %. There is considerable early retention in soft tissues. However, the long-term reservoir for accumulation is bone. It is only very weakly accumulated by aquatic organisms, typically exhibiting concentration ratios relative to water in the range 1 to 5.

Effects on organisms

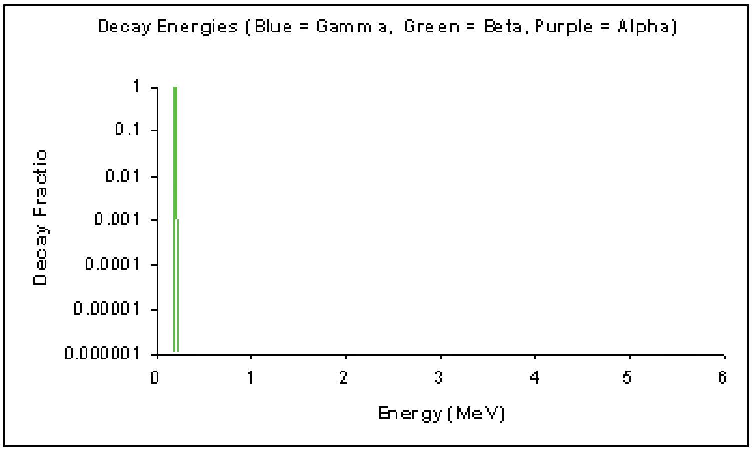
Dose effects/dosimetry	Species-specific considerations
Sr-89 is almost a pure beta emitter. Therefore, externally deposited Sr-89 only irradiates superficial tissues, which are not always very radiosensitive. However, the radionuclide is relatively highly bioavailable, so internal irradiation is likely to be the dominant consideration in animals. In plants, either external or internal irradiation may be more important, depending on the morphology and physiology of the plant, and the characteristics of the deposit.	Accumulation in terrestrial animals seems likely to be of greater interest than uptake in terrestrial plants or aquatic organisms.

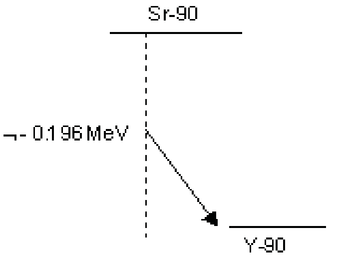
Name	Strontium-90	*Symbol*	Sr-90	*Origin*	Fission
Radioactive half-life	29.1 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Y-90 [R]	*Detection*	Laboratory

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• As an energy source for powering remote machinery e.g. satellites • In medicine for the treatment of cancer
Modes of release	Land	• Deposition onto soils from weapons testing or nuclear accidents
	Air	• As a result of a nuclear accident or historic weapons testing
	Water	• Liquid discharges from nuclear facilities

Decay modes





Average beta energy = 0.196 MeV

Chemical properties/characteristics

Speciation	Analogue species
Strontium is an alkaline earth element and thus the most important species is the Sr^{2+} ion. Isotopes of strontium can therefore be expected to take part in a number of precipitation and substitution reactions. Precipitation as sulphate, carbonate or hydroxide is possible.	The alkaline earths Ca, Sr, Ba and Ra exhibit considerable chemical, biochemical and biogeochemical similarities. Ratios of Sr-90 to stable Ca have often been used to characterise the environmental behaviour of the radionuclide.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Sr-90 is only weakly to moderately particle reactive in soils. Foliar uptake of Sr-90 uptake can be significant, but the radionuclide tends to remain in the plant part where it was deposited and does not become widely translocated.	Sr-90 has only a limited tendency to bind to sediments in either freshwater or marine systems.	Sr-90 would be expected to disperse as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Although Sr-90 is relatively mobile, it can often remain in soils and sediments close to its point of deposition until it decays. However, in freshwater and marine environments, it may be widely dispersed before decaying in the water column and bottom sediments.	Sr-90 is moderately bioavailable to plants. Strontium is moderately bioavailable to animals, with a fractional gastrointestinal absorption of ~20 %. There is considerable early retention in soft tissues. However, the long-term reservoir for accumulation is bone. It is only very weakly accumulated by aquatic organisms, typically exhibiting concentration ratios relative to water in the range 1 to 5.

Effects on organisms

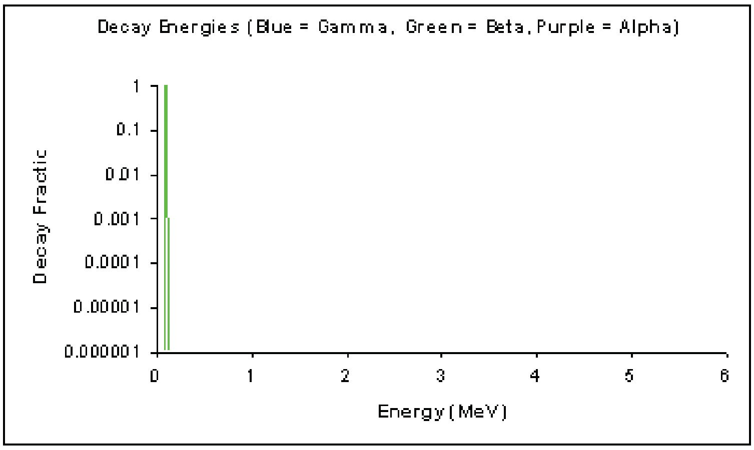
Dose effects/dosimetry	Species-specific considerations
Sr-90 and its short-lived daughter Y-90 are almost pure beta emitters. However, the beta particles from Y-90 are particularly energetic, so more penetration of superficial tissues from external deposits occurs than with most beta emitters. However, Sr-90 is relatively highly bioavailable and long-lived, so internal irradiation is likely to be the dominant consideration in both plants and animals.	Accumulation in terrestrial animals seems likely to be of greater interest than uptake in terrestrial plants or aquatic organisms.

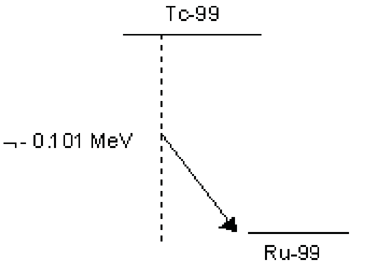
Name	Technetium-99	*Symbol*	Tc-99	*Origin*	Fission
Radioactive half-life	2.1 x 10^5 years	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	Mo-99, Tc-99m	*Daughter*	Ru-99	*Detection*	Laboratory

Production, uses and modes of release

Production		• As a result of fission processes in a nuclear reactor
Uses		• Sometimes used to reduce corrosion of steels
Modes of release	Land	• Present in soils due to fallout from weapons testing
	Air	• Discharged to air from operating nuclear reactors
	Water	• Liquid discharges from nuclear facilities

Decay modes





Average beta energy = 0.101 MeV

Chemical properties/characteristics

Speciation	Analogue species
Technetium can exist in a number of oxidation states, although +7 and +4 are the most stable forms in solution. In oxidising conditions, the pertechnetate ion (TcO_4^-) is the most stable form. It gives rise to salts that are stable in the pH range 0 to 14, and which are generally very soluble. In reducing conditions, oxides of technetium are the dominant form of the element.	Technetium exhibits complex chemical, biochemical and biogeochemical interactions. It is, therefore, strongly recommended that analogies be used only with extreme caution when attempting to characterise the environmental behaviour of technetium.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Tc-99 could be strongly accumulated in strongly reducing soils and sediments. In oxic conditions, however, it is likely to be present as the pertechnetate and to be highly mobile.	Tc-99 reacts only weakly with particulate matter in oxidising conditions, but can be highly particle reactive in reducing conditions. Discharges to freshwater, estuarine or marine environments would be expected to disperse widely, mixing throughout the worldís oceans in the long term.	Sr-90 would be expected to disperse as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its redox-sensitive characteristics, highly reduced soils and sediments can be a sink for Tc-99. However, if the Tc remains in oxic form, it is likely to be highly mobile. In the marine environment, it will largely remain present in the water column until it decays.	In oxic conditions, Tc-99 is highly available to plants and considerable accumulation can occur. Tc can be highly available to animals, with fractional gastrointestinal values approaching 100 %. Tc entering the systemic circulation is widely distributed throughout soft tissues, but is not well retained. Concentration ratios relative to water for Tc are about 30 for freshwater and marine fish, but are about 1,000 for molluscs, crustaceans and seaweed.

Effects on organisms

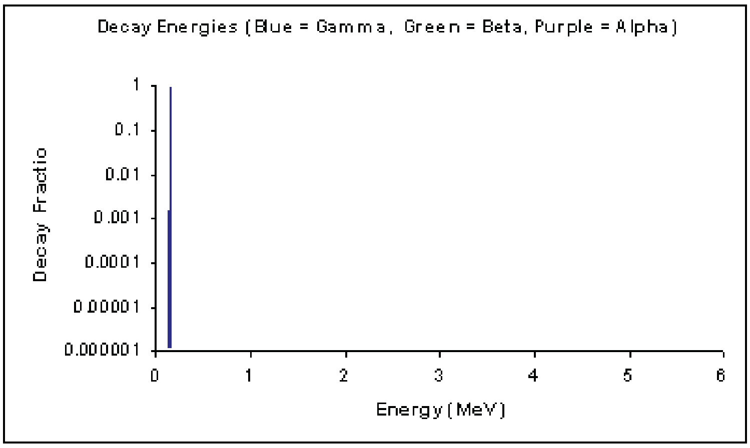
Dose effects/dosimetry	Species-specific considerations
Tc-99 is a soft beta emitter. Therefore, external irradiation is not a consideration. As Tc-99 distributes relatively uniformly throughout body tissues, doses to individual organs and tissues will be of the same order of magnitude as average whole-body doses.	The high concentration ratios exhibited by molluscs, crustaceans and seaweed mean that these species should be given special consideration. Lettuce and spinach have also been observed to exhibit particularly high concentration ratios.

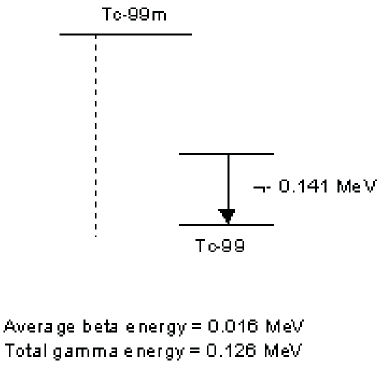
Name	Technetium-99m	*Symbol*	Tc-99m	*Origin*	Fission
Radioactive half-life	6.02 hours	*Principal decay mode*	IT	*Grouping*	Artificial
Parent	Mo-99	*Daughter*	Tc-99 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Irradiation of molybdenum with neutrons in a nuclear reactor or cyclotron
Uses		• In medicine for diagnostic purposes • Assessing the results of surgery and medical treatment
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Technetium can exist in a number of oxidation states, although +7 and +4 are the most stable forms in solution. In oxidising conditions, the pertechnetate ion (TcO_4^-) is the most stable form. It gives rise to salts that are stable in the pH range 0 to 14, and which are generally very soluble. In reducing conditions, oxides of technetium are the dominant form of the element.	Technetium exhibits complex chemical, biochemical and biogeochemical interactions. It is, therefore, strongly recommended that analogies be used only with extreme caution when attempting to characterise the environmental behaviour of technetium.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Tc-99m could be strongly accumulated in strongly reducing soils and sediments. In oxic conditions, however, it is likely to be present as the pertechnetate and to be highly mobile. In oxic conditions, Tc-99 is highly available to plants	Tc-99m reacts only weakly with particulate matter in oxidising conditions, but can be highly particle reactive in reducing conditions. Discharges to freshwater, estuarine or marine environments would be expected to disperse widely.	If Tc-99m were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The very short half-life means that Tc-99m will decay in situ in the terrestrial environment. In aquatic environments, it may disperse a few kilometres before decaying in the water column.	The very short half-life of Tc-99m means that it will have little opportunity to be transferred to terrestrial animals or aquatic organisms. However, following a release to air, Tc-99m would be present on the surfaces of plants and could be subject to some foliar absorption.

Effects on organisms

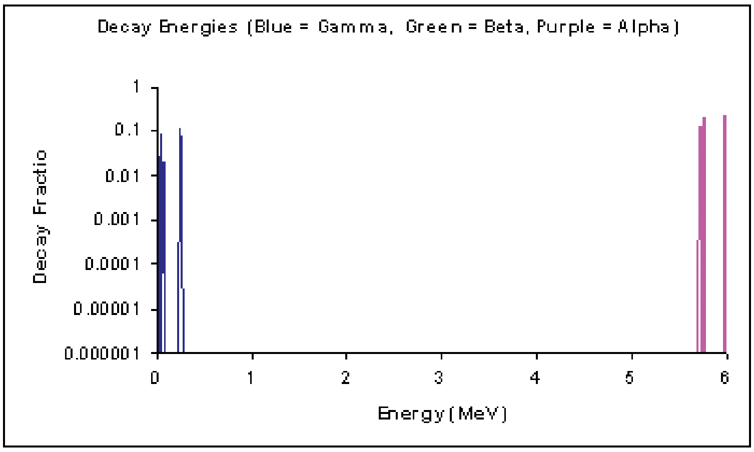
Dose effects/dosimetry	Species-specific considerations
Tc-99m is mainly a gamma emitter. Therefore, external exposure following deposition in a terrestrial environment may be of greater significance than internal exposure, given the limited time for plant or animal uptake.	The high concentration ratios exhibited by molluscs, crustaceans and seaweed mean that these species should be given special consideration. Lettuce and spinach have also been observed to exhibit particularly high concentration ratios.

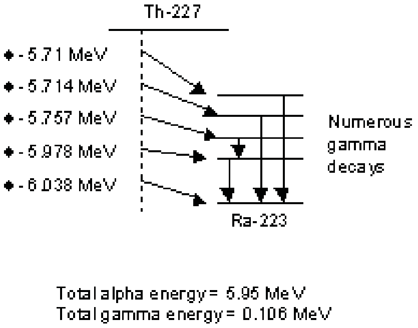
Name	Thorium-227	*Symbol*	Th-227	*Origin*	Radiogenic
Radioactive half-life	18.7 days	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Ac-227	*Daughter*	Ra-223 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of Ac-227, arising from the decay of U-235
Uses		• No specific uses for Th-227
Modes of release	Land	• From the decay of naturally occurring U-235 in soils and rocks • Reprocessing of spent fuel
	Air	• Treatment, reprocessing and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The chemistry of thorium is determined predominantly by the properties of the +4 oxidation state. Thorium salts tend to hydrolyse in water. Thorium forms oxide, chloride, nitrate and sulphate compounds, and can also participate in the formation of organic complexes.	There are similarities between the chemical, biochemical and biogeochemical properties of Th and those of Pu. However, a considerable amount is known about the environmental behaviour of Th, so it is best considered in its own right.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Thorium is very highly particle reactive in terrestrial environments and is strongly adsorbed to all soil types. It is very strongly excluded from plants.	Thorium is very highly particle reactive in aquatic environments and may tend to adsorb to suspended sediments. It would migrate to bottom sediments by deposition.	If Th-227 were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Th-227 will decay close to its site of production in terrestrial environments. In aquatic environments, it will either decay in the water column or in deposited sediments.	Thorium is very strongly excluded from plants. The main route of intake by animals is likely to be ingestion of soil or sediment. Thorium is also of very limited bioavailability in animals. The fractional gastrointestinal absorption is typically <0.1 %. The Th-227 that does enter the systemic circulation is mainly deposited in bone, with the liver and kidneys as secondary sites of deposition. It is relatively highly accumulated in aquatic organisms. These typically exhibit concentration ratios relative to water of around 1,000 in both freshwater and marine environments.

Effects on organisms

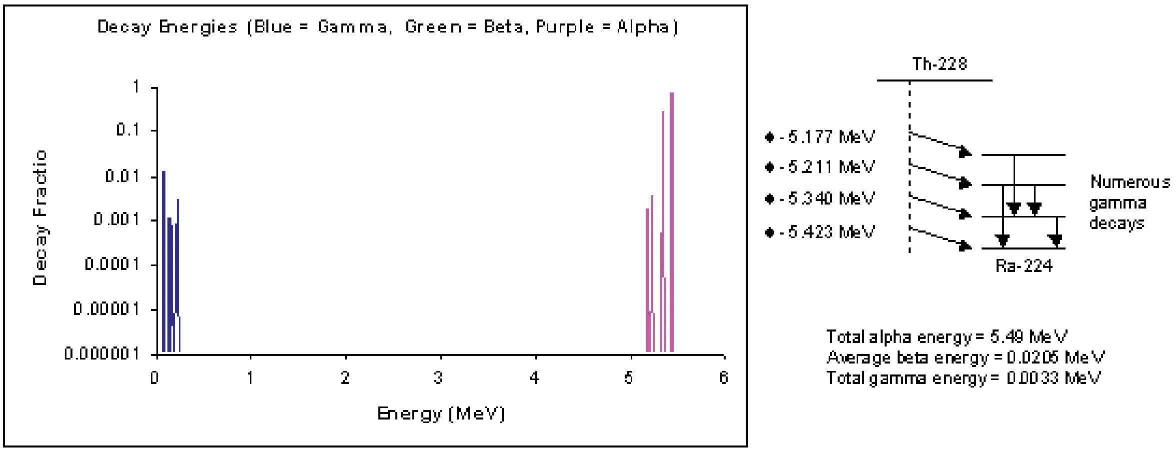
Dose effects/dosimetry	Species-specific considerations
Th-227 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Th-227 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

Name	Thorium-228	*Symbol*	Th-228	*Origin*	Radiogenic
Radioactive half-life	1.9 years	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Ac-228	*Daughter*	Ra-224 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of Ac-228 arising from naturally occurring Th-232
Uses		• No specific uses for Th-228
Modes of release	Land	• From the decay of naturally occurring Th-232 in soils and rocks
	Air	• Treatment and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes



Chemical properties/characteristics

Speciation	Analogue species
The chemistry of thorium is determined predominantly by the properties of the +4 oxidation state. Thorium salts tend to hydrolyse in water. Thorium forms oxide, chloride, nitrate and sulphate compounds, and can also participate in the formation of organic complexes.	There are similarities between the chemical, biochemical and biogeochemical properties of Th and those of Pu. However, a considerable amount is known about the environmental behaviour of Th, so it is best considered in its own right.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Thorium is very highly particle reactive in terrestrial environments and is strongly adsorbed to all soil types. It is very strongly excluded from plants.	Thorium is very highly particle reactive in aquatic environments and would tend to adsorb to suspended sediments. It would migrate to bottom sediments by deposition.	If Th-228 were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Th-228 will decay close to its site of production in terrestrial environments. In aquatic environments, it will either decay in the water column or in deposited sediments.	Thorium is very strongly excluded from plants. The main route of intake by animals is likely to be ingestion of soil or sediment. Thorium is also of very limited bioavailability in animals. The fractional gastrointestinal absorption is typically <0.1 %. The Th-228 that does enter the systemic circulation is mainly deposited in bone, with the liver and kidneys as secondary sites of deposition. It is relatively highly accumulated in aquatic organisms. These typically exhibit concentration ratios relative to water of around 1,000 in both freshwater and marine environments.

Effects on organisms

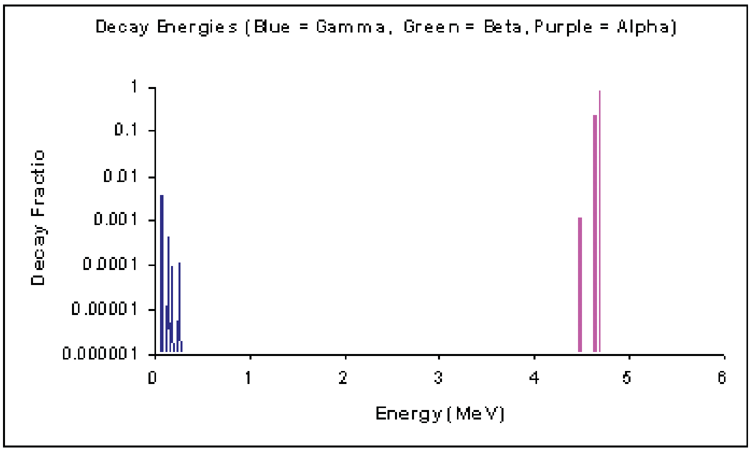
Dose effects/dosimetry	Species-specific considerations
Th-228 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Th-228 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

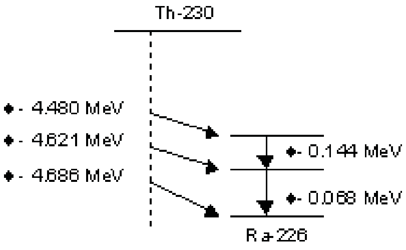
Name	Thorium-230	*Symbol*	Th-230	*Origin*	Radiogenic
Radioactive half-life	7.7 x 10^4 years	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	U-234	*Daughter*	Ra-226 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of U-234 in nature and in nuclear reactors
Uses		• No specific uses for Th-230
Modes of release	Land	• From the decay of U-234 in soils and rocks
	Air	• Treatment and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes





Total alpha energy = 4.74 MeV
Average beta energy = 0.015 MeV
Total gamma energy = 0.0016 MeV

Chemical properties/characteristics

Speciation	Analogue species
The chemistry of thorium is determined predominantly by the properties of the +4 oxidation state. Thorium salts tend to hydrolyse in water. Thorium forms oxide, chloride, nitrate and sulphate compounds, and can also participate in the formation of organic complexes.	There are similarities between the chemical, biochemical and biogeochemical properties of Th and those of Pu. However, a considerable amount is known about the environmental behaviour of Th, so it is best considered in its own right.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Thorium is very highly particle reactive in terrestrial environments and is strongly adsorbed to all soil types. It is very strongly excluded from plants.	Thorium is very highly particle reactive in aquatic environments and would tend to adsorb to suspended sediments. It would migrate to bottom sediments by deposition.	If Th-230 were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The distribution of Th-230 in the environment will usually be similar to that of uranium. However, when Th-230 is produced from U-234 in solution, e.g. in groundwaters, it will be preferentially lost to solids by adsorption. Th-230 originating in, or adsorbed to, solids will generally decay in situ.	Thorium is very strongly excluded from plants. The main route of intake by animals is likely to be ingestion of soil or sediment. Thorium is also of very limited bioavailability in animals. The fractional gastrointestinal absorption is typically <0.1 %. The Th-230 that does enter the systemic circulation is mainly deposited in bone, with the liver and kidneys as secondary sites of deposition. It is relatively highly accumulated in aquatic organisms. These typically exhibit concentration ratios relative to water of around 1,000 in both freshwater and marine environments.

Effects on organisms

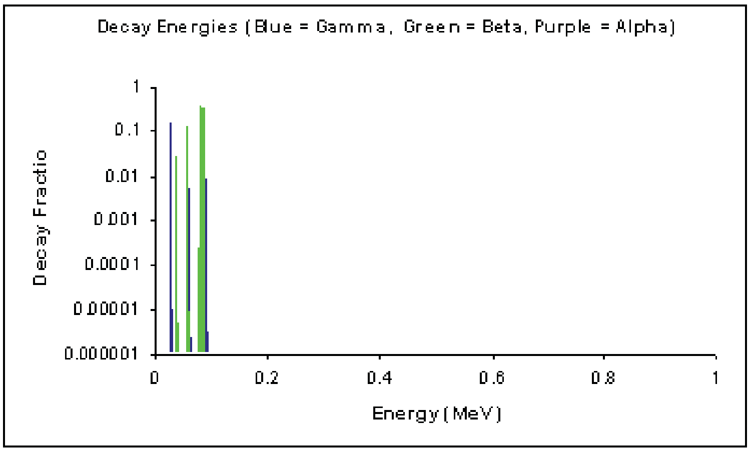
Dose effects/dosimetry	Species-specific considerations
Th-230 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Th-230 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

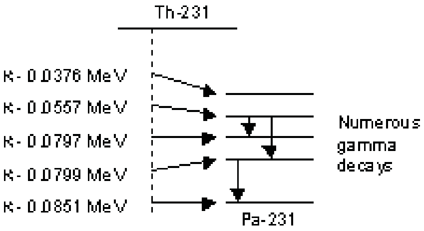
Name	Thorium-231	*Symbol*	Th-231	*Origin*	Radiogenic
Radioactive half-life	25.5 hours	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	U-235	*Daughter*	Pa-231 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of U-235
Uses		• No specific uses for Th-231
Modes of release	Land	• From the decay of U-235 in soils and rocks
	Air	• Treatment and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes





Average beta energy = 0.163 MeV
Total gamma energy = 0.0255 MeV

Chemical properties/characteristics

Speciation	Analogue species
The chemistry of thorium is determined predominantly by the properties of the +4 oxidation state. Thorium salts tend to hydrolyse in water. Thorium forms oxide, chloride, nitrate and sulphate compounds, and can also participate in the formation of organic complexes.	There are similarities between the chemical, biochemical and biogeochemical properties of Th and those of Pu. However, a considerable amount is known about the environmental behaviour of Th, so it is best considered in its own right.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Thorium is very highly particle reactive in terrestrial environments and is strongly adsorbed to all soil types. It is very strongly excluded from plants.	Thorium is very highly particle reactive in aquatic environments and would tend to adsorb to suspended sediments. It would migrate to bottom sediments by deposition.	If Th-231 were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Th-231 will decay close to its site of production in terrestrial environments. In aquatic environments, it will either decay in the water column or in deposited sediments.	Thorium is very strongly excluded from plants. The main route of intake by animals is likely to be ingestion of soil or sediment. Thorium is also of very limited bioavailability in animals. The fractional gastrointestinal absorption is typically <0.1 %. The Th-231 that does enter the systemic circulation is mainly deposited in bone, with the liver and kidneys as secondary sites of deposition. It is relatively highly accumulated in aquatic organisms. These typically exhibit concentration ratios relative to water of around 1,000 in both freshwater and marine environments.

Effects on organisms

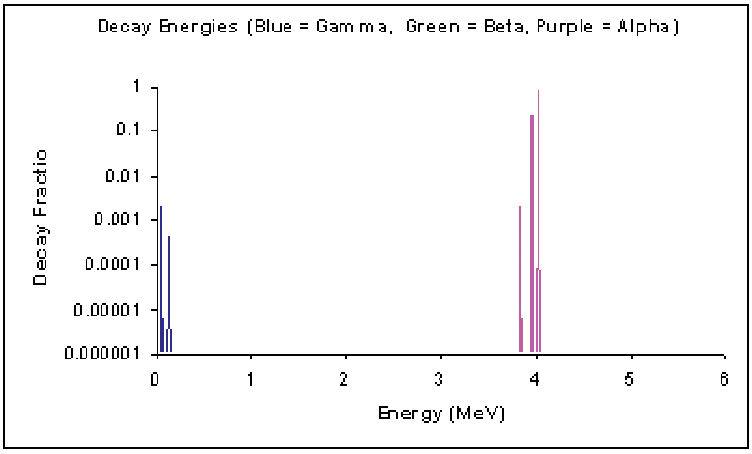
Dose effects/dosimetry	Species-specific considerations
As a short-lived radionuclide emitting primarily low energy beta particles and gamma rays, Th-231 is of little environmental significance in its own right. It is mainly of interest as the immediate parent of Pa-231.	No major species-specific considerations have been identified.

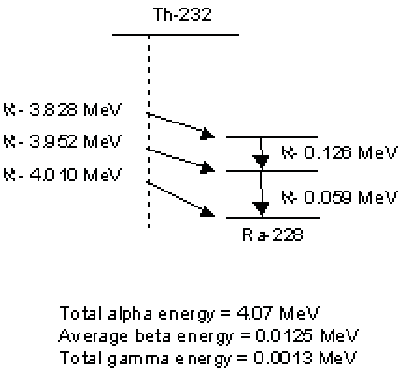
Name	Thorium-232	*Symbol*	Th-232	*Origin*	Primordial
Radioactive half-life	1.41 x 10^{10} yrs	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	U-236	*Daughter*	Th-228 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Naturally during the formation of the Universe • From the decay of U-236
Uses		• Manufacture of gas mantles (Thorium oxide) • As a basis for production of fissionable U-233
Modes of release	Land	• From naturally occurring Th-232 in soils and rocks
	Air	• Treatment and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The chemistry of thorium is determined predominantly by the properties of the +4 oxidation state. Thorium salts tend to hydrolyse in water. Thorium forms oxide, chloride, nitrate and sulphate compounds, and can also participate in the formation of organic complexes.	There are similarities between the chemical, biochemical and biogeochemical properties of Th and those of Pu. However, a considerable amount is known about the environmental behaviour of Th, so it is best considered in its own right.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Thorium is very highly particle reactive in terrestrial environments and is strongly adsorbed to all soil types. It is very strongly excluded from plants.	Thorium is very highly particle reactive in aquatic environments and would tend to adsorb to suspended sediments. It would migrate to bottom sediments by deposition.	If Th-232 were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Th-232 is widely distributed in the environment. However, it is largely incorporated in minerals and tends to be very immobile.	Thorium is very strongly excluded from plants. The main route of intake by animals is likely to be ingestion of soil or sediment. Thorium is also of very limited bioavailability in animals. The fractional gastrointestinal absorption is typically <0.1 %. The Th-232 that does enter the systemic circulation is mainly deposited in bone, with the liver and kidneys as secondary sites of deposition. It is relatively highly accumulated in aquatic organisms. These typically exhibit concentration ratios relative to water of around 1,000 in both freshwater and marine environments.

Effects on organisms

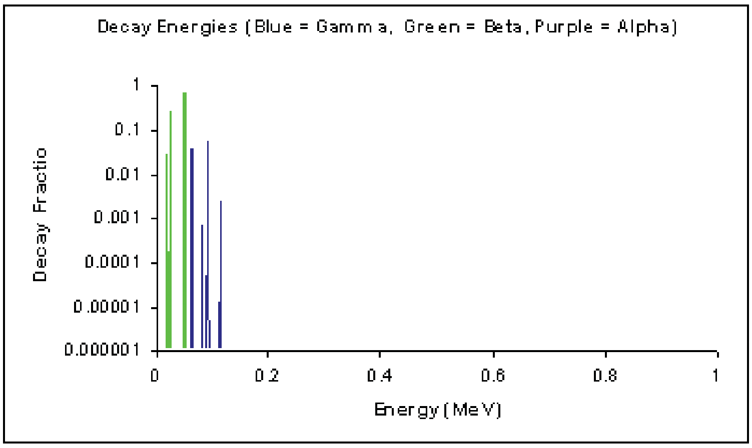
Dose effects/dosimetry	Species-specific considerations
Th-232 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, Th-232 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation.	No species-specific considerations

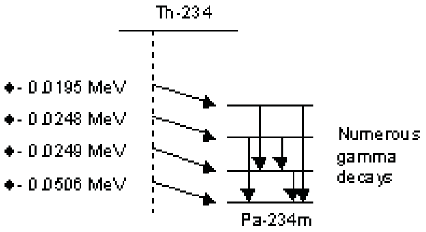
Name	Thorium-234	*Symbol*	Th-234	*Origin*	Radiogenic
Radioactive half-life	24.1 days	*Principal decay mode*	Beta	*Grouping*	Natural
Parent	U-238	*Daughter*	Pa-234m [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of U-238
Uses		• No specific uses for Th-234
Modes of release	Land	• Disposed uranium mill tailings and debris • From naturally occurring U-238 in soil and rocks
	Air	• Treatment and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes





Average beta energy = 0.059 MeV
Total gamma energy = 0.009 MeV

Chemical properties/characteristics

Speciation	Analogue species
The chemistry of thorium is determined predominantly by the properties of the +4 oxidation state. Thorium salts tend to hydrolyse in water. Thorium forms oxide, chloride, nitrate and sulphate compounds, and can also participate in the formation of organic complexes.	There are similarities between the chemical, biochemical and biogeochemical properties of Th and those of Pu. However, a considerable amount is known about the environmental behaviour of Th, so it is best considered in its own right.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Thorium is very highly particle reactive in terrestrial environments and is strongly adsorbed to all soil types. It is very strongly excluded from plants.	Thorium is very highly particle reactive in aquatic environments and would tend to adsorb to suspended sediments. It would migrate to bottom sediments by deposition.	If Th-234 were released to the atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
The distribution of Th-234 in the environment will usually be similar to that of U-238. However, when Th-230 is produced from U-234 in solution, e.g. in groundwaters, it will be preferentially lost to solids by adsorption. Th-234 originating in, or adsorbed to, solids will generally decay in situ.	Thorium is very strongly excluded from plants. The main route of intake by animals is likely to be ingestion of soil or sediment. Thorium is also of very limited bioavailability in animals. The fractional gastrointestinal absorption is typically <0.1 %. The Th-234 that does enter the systemic circulation is mainly deposited in bone, with the liver and kidneys as secondary sites of deposition. It is relatively highly accumulated in aquatic organisms. These typically exhibit concentration ratios relative to water of around 1,000 in both freshwater and marine environments.

Effects on organisms

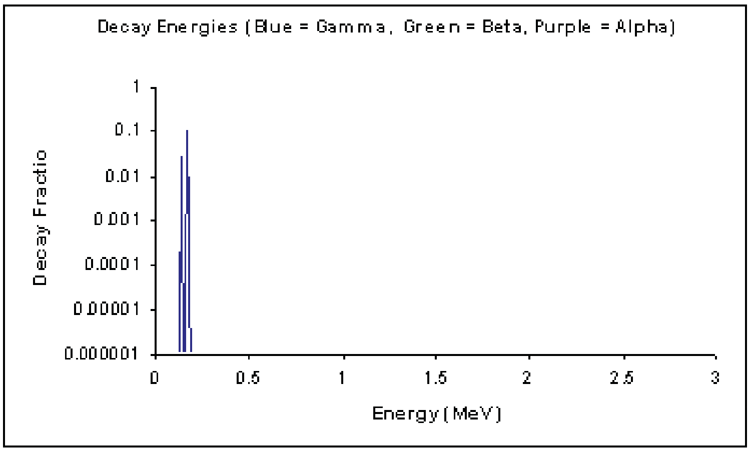
Dose effects/dosimetry	Species-specific considerations
Th-234 is a short-lived beta-gamma emitter. It is of little dosimetric significance compared with its progeny, notably U-234.	No major species-specific considerations have been identified.

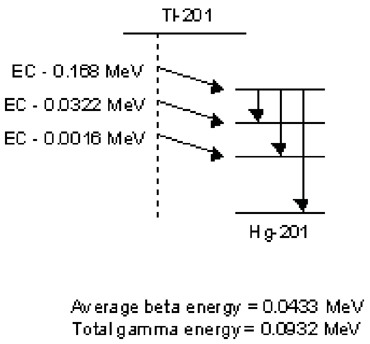
Name	Thallium-201	*Symbol*	Tl-201	*Origin*	Activation
Radioactive half-life	3.04 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Hg-201	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• Sometimes used in medical research and diagnostics
Modes of release	Land	• Sewage sludge application to land, but would probably decay substantially before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Thallium is a Group III element whose dominant oxidation states are +1 and +3. Both states can form oxides, nitrates, sulphates and halides. The +3 oxidation state can readily form complexes.	Biochemically, Tl mimics K, which it resembles in size and ionic charge. In mammals, it is an insidious poison because it affects K-activated enzymes in the brain, muscles and skin.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Tl-201 is likely to bind strongly to the clay fraction of soils. However, because of its short half-life, it is likely to be mainly of interest in terms of foliar deposition.	By analogy with K, Tl-201 would be expected to be readily available to aquatic organisms.	If Tl-201 were released to atmosphere, it would be as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Tl-201 in the terrestrial environment is likely to decay in situ. Dispersion in aquatic environments will be limited by its short half-life and it will decay mainly in the water column	Some uptake of foliar-deposited Tl-201 may occur, but this has not been measured. Tl-201 is highly bioavailable to animals. It is completely absorbed from the gastrointestinal tract in mammals and becomes relatively uniformly distributed throughout the body. It is likely to be concentrated in the muscle of freshwater fish.

Effects on organisms

Dose effects/dosimetry	Species-specific considerations
Tl-201 is primarily a gamma-emitting radionuclide. Because of its short half-life, external irradiation in terrestrial environments may be more important than internal irradiation.	No major species-specific considerations have been identified.

Name	Total alpha	*Symbol*	Total alpha	*Origin*	Various
Radioactive half-life	Various	*Principal decay mode*	Various	*Grouping*	Various
Parent	Various	*Daughter*	Various	*Detection*	Various

Production, uses and modes of release

Production		• Neutron irradiation of uranium and plutonium (post-actinides) • Decay of post-actinides or naturally occurring isotopes
Uses		• Various
Modes of release	Land	• Various, e.g. treatment of spent fuel
	Air	• Various, e.g. treatment of spent fuel
	Water	• Various, e.g. treatment of spent fuel

Chemical properties/characteristics

Speciation	Analogue species
The compounds formed by the different types of alpha emitter will depend on the species under consideration. More information can be found under the individual radionuclide entries.	Alpha emitters arise mainly in the actinide series, so they exhibit a number of chemical similarities to each other. However, the range of elements (including Po, Rn, Ra, Th, U, Np, Pu, Am and Cm) is too wide for any general statement to be made concerning analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
The behaviour of alpha emitters in the environment is most appropriately discussed in the context of individual radioisotopes of Po, Rn, Ra, Th, U, Np, Pu, Am and Cm.		

Exposure routes and pathways

Environmental sink	Intake and uptake routes
As above	As above. Also, most alpha emitters exhibit low bioavailability in both terrestrial plants and animals. However, alpha emitters often accumulate strongly in marine invertebrates and seaweed.

T

Effects on organisms

Dose effects/dosimetry	Species-specific considerations
Species-specific considerations Unless alpha emitters also emit substantial amounts of gamma radiation, which is unusual, they are almost exclusively of relevance in the context of internal irradiation.	As above

Name	Total beta	*Symbol*	Total beta	*Origin*	Various
Radioactive half-life	Various	*Principal decay mode*	Various	*Grouping*	Various
Parent	Various	*Daughter*	Various	*Detection*	Various

Production, uses and modes of release

Production		• Various, e.g. activation and fission
Uses		• Various, including medical and engineering applications
Modes of release	Land	• Various
	Air	• Various
	Water	• Various

Chemical properties/characteristics

Speciation	Analogue species
The compounds formed by the different types of beta emitter will depend on the species under consideration. More information can be found under the individual radionuclide entries.	Beta emitters comprise radioisotopes of elements with a very wide range of chemical, biochemical and geochemical characteristics. Therefore, no generalisations can be made.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
In some circumstances, enquiry can establish that total beta actually relates to a limited number of radionuclides. If this is the case, reference can be made to radionuclide-specific datasheets. The general category of total beta without further characterisation is of little utility.		

Exposure routes and pathways

Environmental sink	Intake and uptake routes
See above	See above

Effects on organisms

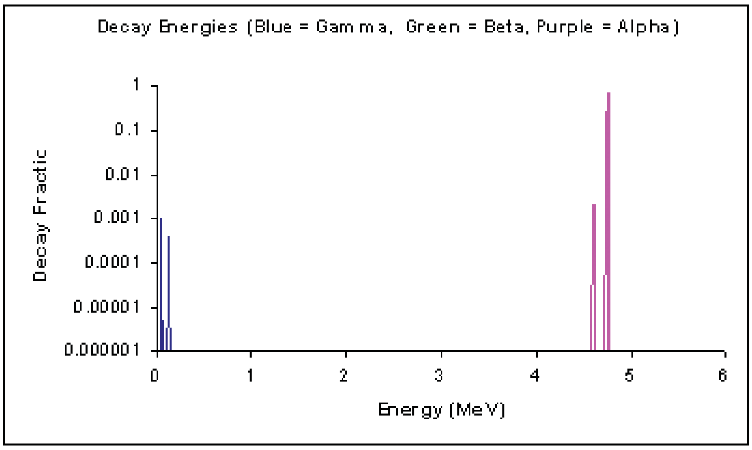
Dose effects/dosimetry	Species-specific considerations
Species-specific considerations See above. It should be remembered that many beta emitters are also strong gamma emitters.	See above

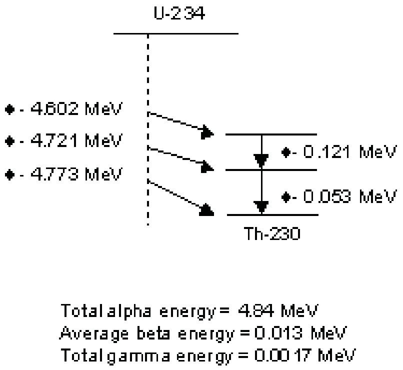
Name	Uranium-234	*Symbol*	U-234	*Origin*	Primordial
Radioactive half-life	2.45 x 10^5 yrs	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Pa-234m, Pu-238	*Daughter*	Th-230 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• From the decay of Pu-238 • From the decay of Pa-234m in the U-238 chain
Uses		• Mainly for research purposes
Modes of release	Land	• Disposed uranium mill tailings and debris; • From naturally occurring U-234 in soil and rocks • Treatment, reprocessing and disposal of spent fuel
	Air	• Treatment, reprocessing and disposal of spent fuel • From burning coal
	Water	• Treatment, reprocessing and disposal of spent fuel

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Uranium can exist in any one of four oxidation states, with the +4 state being favoured in reducing conditions and the +6 state in oxidising conditions. Uranium forms a wide range of halide and oxide compounds. The hydroxide and carbonate are also known and uranium can participate in the formation of organic complexes.	The chemical, biochemical and biogeochemical properties of uranium are quite distinct from those of the other actinide elements and there is a great deal of information on its environmental behaviour. For this reason, there is no requirement to identify analogue elements.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Uranium is not strongly adsorbed to soils. However, its behaviour is redox sensitive and it can accumulate in reducing horizons. In general, it is strongly excluded from plants	Uranium behaves conservatively in aqueous environments. It is not strongly accumulated by aquatic organisms.	U-234 released to atmosphere would be expected to disperse as an aerosol. Chemical forms could include UO_2, U_3O_8 and UF_4. In addition, the toxic gas UF_6 could be released.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
U-234 is produced in the environment from U-238. Almost all of this uranium remains at its site of production until it decays. However, U-234 entering the environment due to human activities may be more mobile, migrating with groundwaters and surface waters until it reaches the aqueous environment.	In general, uranium is strongly excluded from plants, although cereal crops can show a degree of accumulation of uranium. Uranium is not very bioavailable to animals. The fractional gastrointestinal absorption is typically 1%-2 %. Mineral bone is the principal site of accumulation. Concentration ratios relative to water are about 10 for freshwater and marine fish and crustaceans. Concentration ratios for molluscs can be a little higher (~30) and values ~100 are typical of marine plants.

Effects on organisms

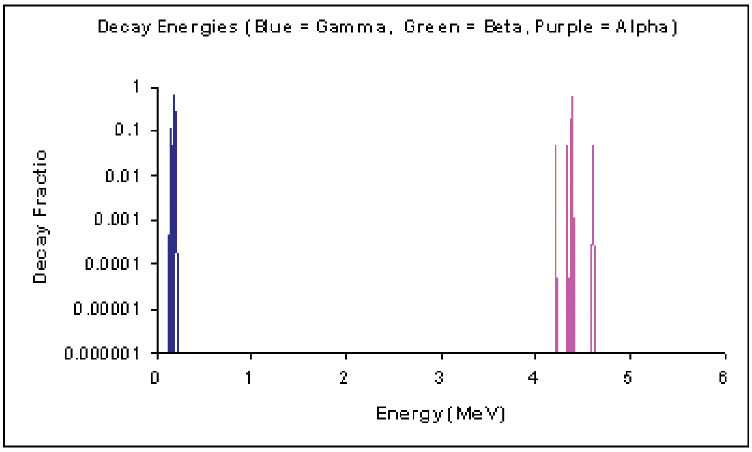
Dose effects/dosimetry	Species-specific considerations
U-234 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, U-234 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation. Note that uranium is chemically toxic as well as posing a radiation hazard.	No major species-specific considerations have been identified.

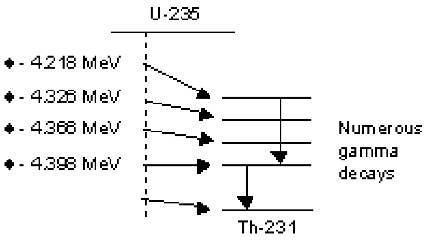
Name	Uranium-235	*Symbol*	U-235	*Origin*	Primordial
Radioactive half-life	7.04 x 10^8 yrs	*Principal decay mode*	Alpha	*Grouping*	Natural
Parent	Pu-239	*Daughter*	Th-231 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Naturally during the formation of the Universe
Uses		• As a basic fuel for nuclear fission reactors
Modes of release	Land	• Treatment and disposal of spent fuel
	Air	• Treatment and disposal of spent fuel • From burning coal
	Water	• Treatment and disposal of spent fuel

Decay modes





Total alpha energy = 4.47 MeV
Average beta energy = 0.048 MeV
Total gamma energy = 0.154 MeV

Chemical properties/characteristics

Speciation	Analogue species
Uranium can exist in any one of four oxidation states, with the +4 state being favoured in reducing conditions and the +6 state in oxidising conditions. Uranium forms a wide range of halide and oxide compounds. The hydroxide and carbonate are also known and uranium can participate in the formation of organic complexes.	The chemical, biochemical and biogeochemical properties of uranium are quite distinct from those of the other actinide elements and there is a great deal of information on its environmental behaviour. For this reason, there is no requirement to identify analogue elements.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Uranium is not strongly adsorbed to soils. However, its behaviour is redox sensitive and it can accumulate in reducing horizons.	Uranium behaves conservatively in aqueous environments. It is not strongly accumulated by aquatic organisms.	U-235 released to atmosphere would be expected to disperse as an aerosol. Chemical forms could include UO_2, U_3O_8 and UF_4. In addition, the toxic gas UF_6 could be released.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
U-235 is a primordial radionuclide widely distributed in rocks, soils and sediments. As it is incorporated in the mineral phase, it tends to remain in situ. U-235 entering the environment due to human activities may be more mobile.	In general, uranium is strongly excluded from plants, although cereal crops can show a degree of accumulation of uranium. Uranium is not very bioavailable to animals. The fractional gastrointestinal absorption is typically 1%-2 %. Mineral bone is the principal site of accumulation. Concentration ratios relative to water are about 10 for freshwater and marine fish and crustaceans. Concentration ratios for molluscs can be a little higher (~30) and values ~100 are typical of marine plants.

Effects on organisms

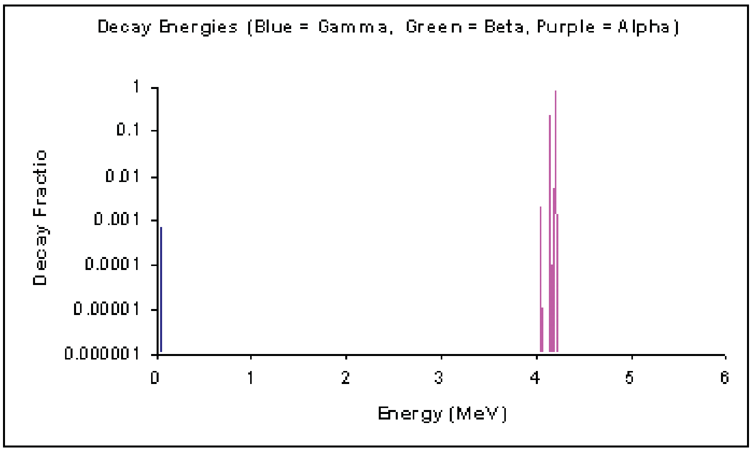
Dose effects/dosimetry	Species-specific considerations
U-235 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, U-235 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation. Note that uranium is chemically toxic as well as posing a radiation hazard.	No species-specific considerations

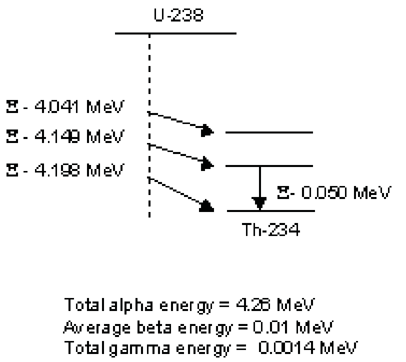
Name	Uranium-238	*Symbol*	U-238	*Origin*	Natural
Radioactive half-life	4.47 x 10^{10} yrs	*Principal decay mode*	Alpha	*Grouping*	Primordial
Parent	Pu-242	*Daughter*	Th-234 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Naturally during the formation of the Universe
Uses		• As the starting point for production of Pu-239 • For the production of armour-piercing munitions
Modes of release	Land	• Disposed uranium mill tailings and debris • From naturally occurring U-238 in soil and rocks • Treatment, reprocessing and disposal of spent fuel
	Air	• Treatment, reprocessing and disposal of spent fuel • From burning coal
	Water	• Treatment, reprocessing and disposal of spent fuel

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Uranium can exist in any one of four oxidation states, with the +4 state being favoured in reducing conditions and the +6 state in oxidising conditions. Uranium forms a wide range of halide and oxide compounds. The hydroxide and carbonate are also known and uranium can participate in the formation of organic complexes.	The chemical, biochemical and biogeochemical properties of uranium are quite distinct from those of the other actinide elements and there is a great deal of information on its environmental behaviour. For this reason, there is no requirement to identify analogue elements.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Uranium is not strongly adsorbed to soils. However, its behaviour is redox sensitive and it can accumulate in reducing horizons. In general, it is strongly excluded from plants	Uranium behaves conservatively in aqueous environments. It is not strongly accumulated by aquatic organisms.	U-238 released to atmosphere would be expected to disperse as an aerosol. Chemical forms could include UO_2, U_3O_8 and UF_4. In addition, the toxic gas UF_6 could be released.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
U-238 is a primordial radionuclide widely distributed in rocks, soils and sediments. As it is incorporated in the mineral phase, it tends to remain in situ. U-238 entering the environment due to human activities may be more mobile.	In general, uranium is strongly excluded from plants, although cereal crops can show a degree of accumulation of uranium. Uranium is not very bioavailable to animals. The fractional gastrointestinal absorption is typically 1%-2 %. Mineral bone is the principal site of accumulation. Concentration ratios relative to water are about 10 for freshwater and marine fish and crustaceans. Concentration ratios for molluscs can be a little higher (~30) and values ~100 are typical of marine plants.

Effects on organisms

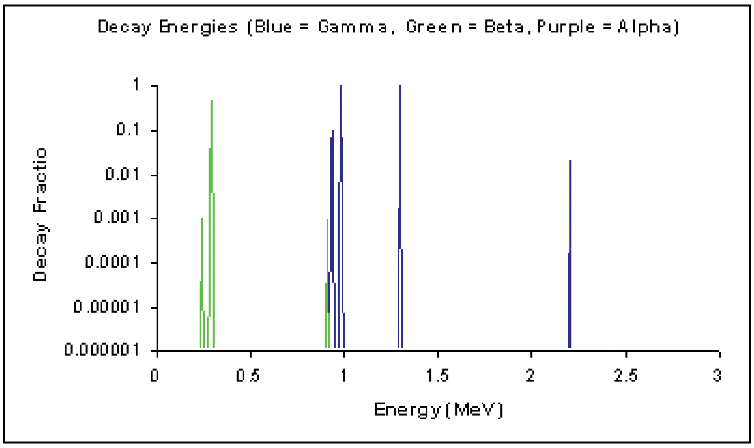
Dose effects/dosimetry	Species-specific considerations
U-238 is primarily an alpha emitter. Activity deposited on the outer layers of organisms (e.g. skin) will therefore be of little radiological consequence. Therefore, U-238 is of greatest potential significance when internally incorporated in organs and tissues that are susceptible to the effects of alpha radiation. Note that uranium is chemically toxic as well as posing a radiation hazard.	No species-specific considerations

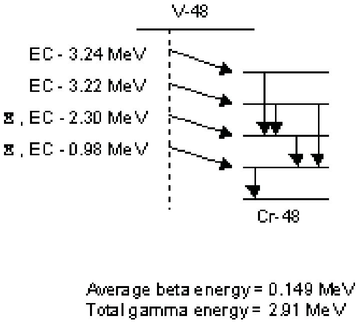
Name	Vanadium-48	*Symbol*	V-48	*Origin*	Activation
Radioactive half-life	16.2 days	*Principal decay mode*	EC	*Grouping*	Artificial
Parent	N/A	*Daughter*	Ti-48	*Detection*	In situ

Production, uses and modes of release

Production		• Irradiation of non-radioactive precursors in a cyclotron or nuclear reactor
Uses		• Certain medical applications, for example delivering radiation doses to arteries inside a stent (mesh container)
Modes	Land	• Sewage sludge application to land
of	Air	• Not generally released to air
release	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Vanadium is a transition metal that can show oxidation states from -1 through to +5. It forms sulphate, oxide and halide compounds. Because of the ability to hold different oxidation states, there are several different forms of sulphate, oxide and halide compounds.	There have been extensive studies on the distribution and transport of vanadium in the environment. Therefore, it is not appropriate to identify any analogues.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Relative to other metals, V is fairly mobile in neutral or alkaline soils, but its mobility is lower in acid soils. Mobility is much higher in oxidising than in reducing conditions.	In freshwater, V-48 is likely to be present as V^{4+} under reducing conditions and V^{5+} under oxidising conditions. Both species are known to bind strongly to mineral or biogenic surfaces. In the oceans, most V is removed from the water column by deposition.	If V-48 is released to atmosphere, it will be in the form of an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Because of its short half-life, V-48 in terrestrial environments is likely to decay in situ. In aquatic systems, V-48 will decay both in the water column and in deposited sediments.	V-48 in the terrestrial environment is likely to be present mainly on the external surfaces of plants following deposition from the atmosphere. Vanadium is of limited bioavailability to animals and the fractional gastrointestinal absorption is ~1 %. Vanadium entering the systemic circulation is preferentially deposited in the skeleton of mammals. Marine plants and invertebrates contain higher concentrations of vanadium than terrestrial plants and animals.

Effects on organisms

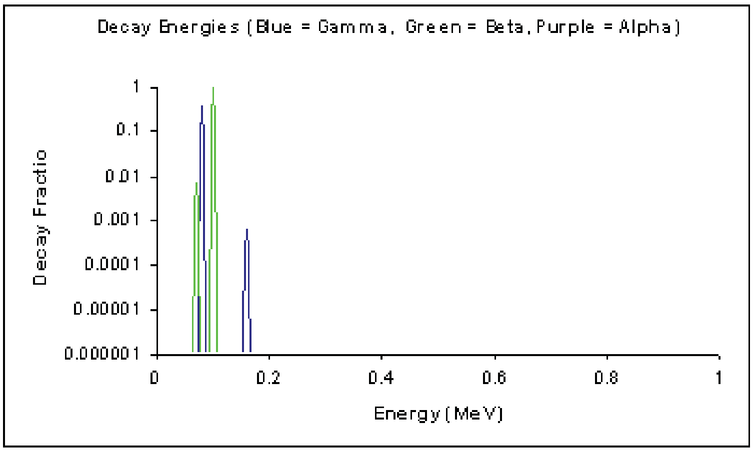
Dose effects/dosimetry	Species-specific considerations
V-48 emits energetic gamma rays. Because of its short half-life and limited bioavailability to many plants and animals in terrestrial environments, external irradiation may be of greater significance than internal irradiation. Similarly, external irradiation from material adsorbed to external surfaces of organisms may be important in the aquatic environment.	There are specific species of higher plants and fungi that accumulate stable V. These may also accumulate V-48.

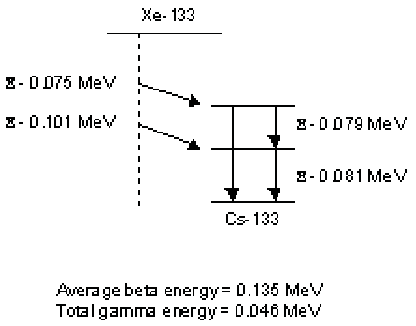
Name	Xenon-133	*Symbol*	Xe-133	*Origin*	Fission
Radioactive half-life	5.2 days	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	N/A	*Daughter*	Cs-133	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor
Uses		• Occasionally used in medicine for diagnostic imaging
Modes of release	Land	• Not generally released to land
	Air	• During treatment and disposal of spent fuel
	Water	• Not generally released to water

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Xenon is a noble gas and, as such, forms only a limited number of chemical compounds due to its lack of reactivity. One such example is XeF_2.	All the noble gases (Ne, Ar, Kr, Xe and Rn) exhibit similar environmental behaviour. Rn is a special case because it is generated in the environment from isotopes of radium and because it decays to produce chemically reactive, short-lived and long-lived radioactive progeny. Rn is therefore not an appropriate analogue for Xe.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Xe-133 is not transferred significantly to the terrestrial environment.	Xe-133 is not transferred significantly to the aquatic environment.	Xe-133 is almost exclusively released to the atmosphere. Its short radioactive half-life and low reactivity means that it decays almost entirely during atmospheric transport and is not transferred significantly to other environmental media.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
No major sink, owing to its lack of reactivity and short half-life.	Xe-133 is sparingly soluble in body tissues, notably those with a high fat content. However, it is not metabolised. Some Xe-133 will be present in the lungs in inhaled air.

Effects on organisms

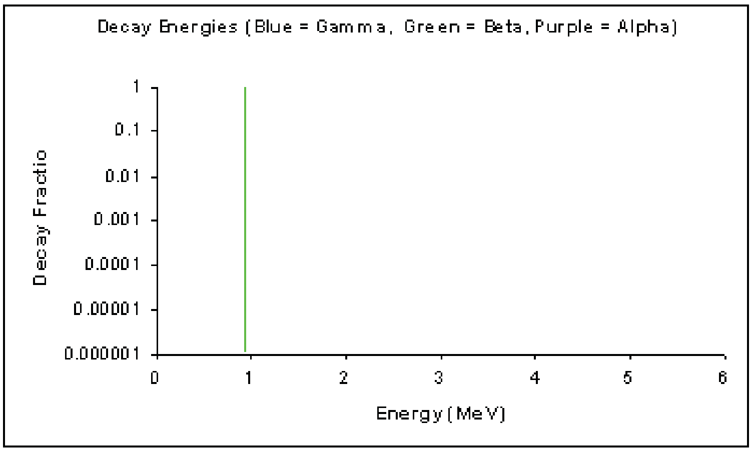
Dose effects/dosimetry	Species-specific considerations
Xe-133 emits beta particles and low energy gamma rays. Radiation doses to organisms arise mainly due to external beta and gamma irradiation, irradiation of the lungs of animals from contained gas and internal irradiation from gas dissolved in tissues.	Because Xe-133 is not metabolised to any significant degree, there are no major species-dependent considerations.

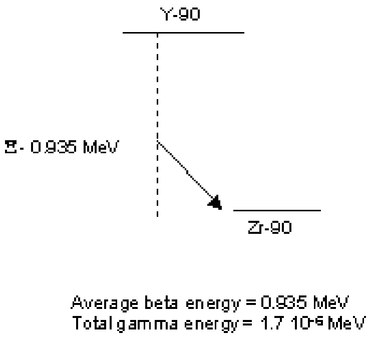
Name	Yttrium-90	*Symbol*	Y-90	*Origin*	Radiogenic
Radioactive half-life	64 hours	*Principal decay mode*	Beta	*Grouping*	Artificial
Parent	Sr-90	*Daughter*	Zr-90	*Detection*	Laboratory

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor • From decay of strontium-90, another important fission isotope
Uses		• In medicine for the treatment of cancer and arthritis
Modes of release	Land	• Sewage sludge application to land, but would probably decay away before this can occur
	Air	• Not generally released to air
	Water	• Hospital releases to sewers

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
Yttrium is a transition metal that only forms compounds in the +3 oxidation state. The chemistry of yttrium is very similar to that of the rare earths. As such, yttrium forms compounds with hydrogen, oxygen and the halides. It also forms a number of stable complexes.	Ce is the most studied of the rare earths and provides a good analogue for the behaviour of Y-90. However, in the environment, Y-90 is usually present as a result of the decay of Sr-90 and its behaviour is often determined by that of its parent.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Y-90 is highly particle reactive and would tend to bind to surfaces when produced.	In aquatic environments, Y-90 produced from Sr-90 would tend to be particle reactive and would, therefore, tend to migrate from the water column by deposition	If Y-90 were released to the atmosphere, it would be in the form of an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
In general, the short half-life and limited mobility of Y-90 will mean that it decays close to its point of production.	In plants and animals, Y-90 is likely to be present in concentrations that are close to secular equilibrium with those of Sr-90. With the assumption of secular equilibrium, intake and uptake routes for Y-90 are of limited importance. As with Sr-90, high concentrations are likely to be found in the skeleton.

Effects on organisms

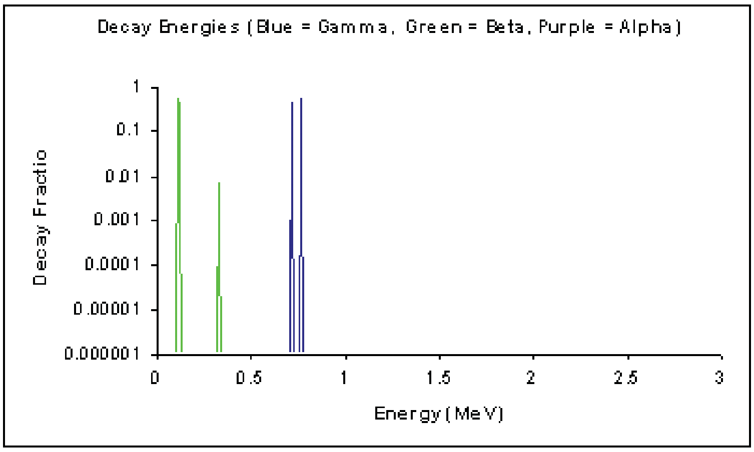
Dose effects/dosimetry	Species-specific considerations
Y-90 is a pure beta emitter. Under the assumption of secular equilibrium, a convenient approach to dosimetry is to assign the Y-90 beta energy to its parent Sr-90.	As for Sr-90

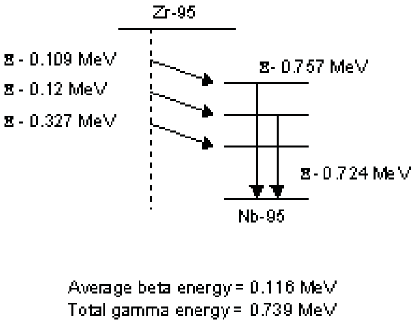
Name	Zirconium-95	*Symbol*	Zr-95	*Origin*	Fission
Radioactive half-life	64 days	*Principal decay mode*	Beta [gamma]	*Grouping*	Artificial
Parent	N/A	*Daughter*	Nb-95 [R]	*Detection*	In situ

Production, uses and modes of release

Production		• Produced during fission in a nuclear reactor • Irradiation of zirconium cladding with neutrons in a nuclear reactor
Uses		• No specific uses outsides research activities
Modes of release	Land	• During treatment and disposal of spent fuel
	Air	• During treatment and disposal of spent fuel
	Water	• During treatment and disposal of spent fuel • Liquid discharges from nuclear facilities

Decay modes





Chemical properties/characteristics

Speciation	Analogue species
The most important oxidation state for zirconium in aqueous solution is +4. However, the Zr^{4+} ion is only soluble in strong (laboratory) acid solutions (pH <1). In water, zirconium hydrolyses very easily to form hydroxo complexes, unless in the form of the very stable fluoride.	There are chemical, biochemical and biogeochemical similarities between Zr and Nb. However, both elements have been studied to a similar degree and there is little merit in treating Zr as an analogue of Nb or vice versa.

Behaviour in the environment

Terrestrial	Aquatic	Atmospheric
Zr-95 is highly particle reactive. It will therefore tend to remain in situ, rather than migrating through the terrestrial environment in surface or groundwaters.	Zr-95 is highly particle reactive in marine systems. In freshwater systems, it has moderate to high particle reactivity. However, even in marine systems, a significant fraction of the Zr-95 may be associated with colloids or dissolved organic matter complexes.	If Zr-95 were released to the atmosphere, it would disperse as an aerosol.

Exposure routes and pathways

Environmental sink	Intake and uptake routes
Zr-95 will generally decay close to its point of deposition in the terrestrial environment. In aquatic systems, Zr-95 will interact with mineral sediments, colloids and dissolved organic matter. Some will be transferred to bottom sediments and decay will occur there or in the water column.	Zr-95 is strongly excluded from plants. It is also not very bioavailable to animals, with a fractional gastrointestinal absorption of ~0.2 %, although this may be increased in pre-weaned juveniles. Zr-95 that enters systemic circulation is widely dispersed in soft tissues, but the main reservoir of uptake and long-term retention is mineral bone. Concentration ratios relative to water are about 20 for freshwater and marine fish, but can be >1,000 for marine invertebrates and seaweed.

Effects on organisms

Dose effects/dosimetry	Species-specific considerations
Zr-95 has a high yield of energetic gamma rays. Because of its low bioavailability in terrestrial environments, external irradiation is likely to be of greater significance than internal irradiation. External irradiation may also be of greatest importance in the aquatic environment.	The main species-specific consideration is the partitioning of Zr-95 in marine invertebrates between adsorbed, unassimilated particulate and tissue uptake fractions.

Glossary

This glossary defines some of the terms used in this publication, but also replicates entries from the glossary found in Copplestone et al. (2001). Other sources, e.g. IAEA (2000), provide a more extensive list of definitions.

Aberration
Departure from normal.

Absorbed dose
Quantity of energy imparted by ionising radiation to unit mass of matter such as tissue. Unit Gray, symbol Gy. 1Gy = 1 joule per kilogram.

Actinides
A group of 15 elements with atomic number from that of actinum (89) to lawrencium (103) inclusive and analogous to the so-called lanthanide series of rare earth metals. All are radioactive. In general, the actinides are highly particle reactive and are not taken up easily by plants or animals. Nevertheless, they are generally very radiotoxic.

Activation
The process in which non-radioactive elements are converted to radioactive elements as a result of exposure to radiation in a nuclear reactor or weapon explosion. An example is the formation of techetium-99m for medical purposes from irradiation of molydenum-99.

Activity
Attribute of an amount of a radionuclide. Describes the rate at which transformations occur in it. Unit Becquerel, symbol Bq. 1Bq = 1 transformation per second.

Acute exposure
Exposure received within a short period of time. Normally used to refer to exposure of sufficiently short duration that the resulting dose can be treated as instantaneous (e.g. less than an hour). Usually contrasted with chronic and transitory exposure.

Adsorb
Usually a solid holding molecules (of a gas or liquid, etc.) to its surface, forming a thin film.

Advanced gas cooled reactor
A development of the Magnox reactor, using enriched uranium oxide fuel in stainless steel cladding.

Aerosol
A suspension of fine solid or liquid particles in gas. Smoke, fog, and mist are examples of aerosols.

Alpha particle
A particle consisting of two protons plus two neutrons, i.e. fast-moving helium nuclei (atomic mass of 4 and atomic number 2). Emitted by a radionuclide.

Allotropy
The ability of certain elements and compounds (e.g. phosphorus) to show two or more distinct physical forms in the same physical state (e.g. solid).

Antineutrino
A particle without mass or charge that is emitted from the nucleus, along with an electron, during beta decay.

Apoptosis
Apoptosis or programmed cell death occurs naturally during the development and maintenance of animal tissues and organs. During these processes, more cells are produced than are required for building tissues and organs. The unwanted cells are programmed to die either because the chemical signals that direct them to go on living are suppressed or because they receive a specific signal to die.

Atom
The smallest portion of an element that can combine chemically with other atoms.

Atomic mass
The mass of an atomic nucleus, usually denoted by the symbol A.

Atomic number
The number of protons within an atomic nucleus, usually denoted by the symbol Z.

Auger electron
A low-energy electron ejected from an atom following the transition of another electron from a higher to lower energy state.

Authorisation
The granting by a regulatory body or other governmental body of written permission for an operator to perform specified activities.

Background
The dose or dose rate (or an observed measure related to the dose or dose rate), attributable to all sources other than the one(s) specified.

Becquerel (Bq)
See activity.

Benthic invertebrate
Aquatic invertebrate living on or in sediment.

Benthos
Synonym for community of benthic invertebrate.

Beta particle
A negatively charged (electron) or positively charged (positron) particle emitted from the nucleus of an atom during radioactive decay. Often loosely assumed to be the negatively charged particle.

Bioavailability
The degree and rate at which a substance is absorbed into a living system or is made available at the site of physiological activity.

Biomarker
A biological response to an environmental pollutant, which gives a measure of exposure. The response may be molecular, cellular or whole organism.

Biota
A collective term for the flora and fauna.

Breeding (in radiation term)
The production of one radionuclide from another due to the action of incident atomic particles, e.g. the production of plutonium-239 from uranium-238.

Chromatid
When a chromosome becomes shorter and thicker during the first stage of mitosis it is seen to become a double thread. Each thread is a chromatid.

Chromosome translocation
Sporadic and random fusion of part of one chromosome onto part of another.

Chromosomes
Rod-shaped bodies found in the nucleus of cells in the body. They contain the genes or hereditary constituents. Each chromosome has a characteristic length and banding pattern.

Chronic exposure
Exposure persisting in time. Normally used to refer to continuous exposures to low concentrations of pollutants. See also transitory and acute exposure.

Concentration factor (CF)
Ratio of element or nuclide in the consumer (or a specific tissue or organ etc.), to that in what is consumed, or to that in the environmental medium.

Cosmic radiation
High energy ionising radiation from outer space.

Cosmogenic
Denoting radionuclides produced in the upper atmosphere due to the action of cosmic rays.

Critical group
Sub-group of the public most affected by a given release of radioactivity.

Critical organ
The organ or tissue the irradiation of which presents the greatest threat to the health of the individual.

Critical pathway
The pathway that leads to the greatest dose of radiation. An example would be the air-grass-cow-milk pathway, important for iodine isotopes released into the air.

Cyclotron
An apparatus for producing high-energy atomic particles.

Cytogenetic damage
Damage to chromosomes that can be detected on the microscopic level. Examples of damage include deletions, translocations and micronuclei.

Decay
The process of spontaneous transformation of a radionuclide. The decrease in the activity of a radioactive substance.

Decay product

A nuclide or radionuclide produced by decay. It may be formed directly from a radionuclide or as a result of a series of successive decays through several radionuclides.

Decommissioning

The process of closing down a nuclear reactor, removing the spent fuel, dismantling some of the other components, and preparing them for disposal. Term may also be applied to other major nuclear facilities.

Deposition

The settling of particles from the atmosphere to the ground or plant surfaces. Deposition can be wet (e.g. through rainfall) or dry.

Deterministic effect

A radiation effect for which generally a threshold level of dose exists above which the severity of the effect is greater for a higher dose.

Disposal

In relation to radioactive waste, dispersal or emplacement in any medium without the intention of retrieval.

DNA

Deoxyribonucleic acid. The compound that controls the structure and function of cells and is the material of inheritance.

Dose

General term for quantity of ionising radiation. See absorbed dose, equivalent dose and effective dose. Frequently used for effective dose.

Dose assessment

Assessment of the dose(s) to an individual or group of people.

Dose rate

Dose released over a specified unit of time.

Effective dose

The quantity obtained by multiplying the equivalent dose to various tissues and organs by a weighting factor appropriate to each and summing the products. Unit Sievert, symbol Sv. Frequently abbreviated to dose.

Electromagnetic radiation

Radiation consisting of electric and magnetic waves that travel at the speed of light. Examples: light, radio waves, gamma rays, x-rays.

Electron

The electron is a small atomic particle with 1 unit of negative electric charge and a mass of $^{1}/_{1836}$ of a proton. Every atom consists of one nucleus and one or more electrons in orbit around the nucleus. Positively charged electrons, called positrons, also exist. See also beta particle.

Electron capture (EC)

A form of radioactive decay in which the nucleus captures an orbiting electron, converting a proton to a neutron, the energy being released as X-rays (or Auger electrons).

Electron volt

Unit of energy employed in radiation physics. Equal to the energy gained by an electron in passing through a potential difference of 1 volt. Symbol eV. 1eV = ~1.6 x 10^{-19} joule.

Embryo (in animals)

The stage of development between the time that the fertilised egg begins to divide and the developing animal hatches or is born.

Embryo (in plants)

The part of a seed which develops into the root (radicle) and shoot (plumule) of a plant.

Embryogenesis

The processes leading to the development of an embryo.

Endpoint

1. The final stage of a process, especially the point at which an effect is observed.
2. A radiological or other measure of protection or safety that is the calculated result of an analysis or assessment.

Enriched uranium

Uranium in which the content of the isotope uranium-235 has been increased above its natural value of 0.7 % by weight.

Equivalent dose

The quantity obtained by multiplying the absorbed dose by a weighting factor (radiation weighting factor) to allow for the different effectiveness of the various ionising radiation in causing harm to tissue. Unit Sievert, symbol Sv.

Fallout

The transfer of radionuclides produced by nuclear weapons from the atmosphere to earth; the material transferred.

Fecundity
The number of viable offspring produced by an organism; mature seeds produced, eggs laid, or live offspring delivered, excluding fertilised embryos that have failed to develop.

Fertility
In sexually reproducing plants and animals, it is the number of fertilised eggs produced in a given time.

Fission
Nuclear fission. A process in which a nucleus splits into two or more nuclei and energy is released. Frequently refers to the splitting of a nucleus of uranium-235 into two approximately equal parts by a thermal neutron with emission of one or more neutrons and the release of energy.

Fission products
The atoms formed as a result of nuclear fission, e.g. caesium-137, iodine-131, strontium-90, cerium-144.

Foetus
The developing embryo is known as a foetus once it can be recognised as a species.

Free radical
A grouping of atoms that normally exists in combination with other atoms but can sometimes exist independently. Generally very reactive in a chemical sense.

Gametes
The sex cells which fuse together at fertilisation to form the zygote. In animals, the gametes are the sperm in males and the ovum (egg) in females. In plants, the gametes are the pollen in the male and the ovules in the female.

Gametogenesis
Process leading to the production of gametes.

Gamma radiation
Very penetrating electromagnetic radiation, without mass or charge, frequently emitted from the nucleus of an atom during radioactive decay. Emitted by a radionuclide.

Genes
The biological units of heredity. They are arranged along the length of chromosomes.

Genotoxicity
Ability to cause damage to genetic material. Such damage may be mutagenic and/or carcinogenic.

Germ cell
Cell specialised to produce gametes. The germ cell line is often formed very early in embryonic development.

Gestation
The process of being carried in the womb, from conception to birth.

Gray (Gy)
See absorbed dose.

High level waste (HLW)
The radioactive liquid containing most of the fission products and actinides present in spent fuel, which forms the residue from the first solvent extraction cycle in reprocessing, and some of the associated waste streams. The term is also used for: this material following solidification; spent fuel (if it is declared a waste); or any other waste with similar radiological characteristics.

Implantation
When an embryo passes from the oviduct to the uterus, it becomes attached to the uterine wall.

Indicator species
A species that only thrives under certain environmental conditions and whose presence shows that these conditions are present.

Inert gas
A member of the family of gaseous chemical elements characterised by their extreme lack of reactivity. The inert gases are: helium, neon, argon, krypton, xenon and radon.

Ion
An atom or group of atoms that carries a net electrical charge - either positive or negative.

Ionisation
The process by which a neutral atom or molecule acquires or loses an electric charge. The production of ions.

Ionising radiation
Radiation that produces ionisation in matter. Examples are alpha particles, gamma rays, X-rays and neutrons. When these pass through the tissues of the body, they have sufficient energy to damage DNA.

Irradiation
Exposed to radiation.

Isomeric transformation (IT)
A form of radioactive decay in which a metastable nucleus decays with the release of energy as gamma rays.

Isomers
In this context, nuclides having the same number of protons and neutrons in their nucleus but in different energy states.

Isotope
Nuclides with the same number of protons but different numbers of neutrons. Not a synonym for nuclide.

Karyotype
The complete set of chromosomes of a cell or organism.

Lanthanides
The group of elements with atomic numbers between Z = 57 and Z = 70. They have similar chemical properties and are highly particle reactive.

LD_{50}
The dose that causes mortality in 50 % of the organisms tested.

Linear energy transfer (LET)
A measure of how, as a function of distance, energy is transferred from radiation to the exposed matter. Radiation with high LET is normally assumed to comprise of protons, neutrons and alpha particles (or other particles of similar or greater mass). Radiation with low LET is assumed to comprise of photons (including X-rays and gamma rays), electrons and positrons.

Low and intermediate level waste (LLW and ILW)
Radioactive waste with radiological characteristics between those of exempt waste and high level waste. These may be long-lived waste (LILW-LL) or short-lived waste (LILW-SL).

Magnox reactor
A thermal reactor named after the magnesium alloy in which the uranium metal fuel is contained. The moderator is graphite and the coolant is carbon dioxide gas.

Meiosis
A form of nuclear division in which each daughter cell receives only one of each homologous chromosome pair. Meiosis occurs during the formation of gametes.

Metabolism
The chemical changes in living cells by which energy is provided for vital processes and activities and new material is assimilated.

Mitosis
A type of cell division by which two daughter cells are produced from one parent cell, with no change in the number of chromosomes.

Moderator
A material used in nuclear reactors to reduce the energy and speed of the neutrons produced as a result of fission.

Molecule
The smallest portion of a substance that can exist by itself and retain the properties of the substance.

Morbidity
The state of being diseased.

Morphogenesis
The process of ëshape formationí: the processes that are responsible for producing the complex shapes of adults from the simple ball of cells that derives from division of the fertilised egg.

Mutation
A change in the genetic material of an organism. This can be spontaneous or induced by chemicals or radiation.

Naturally occurring radionuclides
Radionuclides that occur naturally in significant quantities on Earth.

Neutrino
A particle without mass or charge that is emitted from the nucleus, along with a positron, during beta decay.

Neutron
A fundamental nuclear particle of mass 1 and zero electric charge.

Non-ionising radiation
Radiation that does not produce ionisation in matter. Examples are ultraviolet radiation, light, infrared radiation and radio-frequency radiation. When these radiation pass through the tissues of the body, they do not have sufficient energy to damage DNA directly.

Non-nuclear licensed site

A non-nuclear licensed site (or non-nuclear site) is where the handling, use and discharge of radioactive substances may occur but not as the main activity. This includes research institutions, hospitals, defence establishments, etc.

Nuclear fuel cycle

The stages in which the fuel for nuclear reactors is first prepared, then used, and later reprocessed for possible use again. Waste management is also considered part of the cycle.

Nuclear licensed site

A nuclear licensed site (or nuclear site) holds an operating licence under the Nuclear Installations Act 1965; the handling or use of radioactive materials is the main activity.

Nuclear power

Power obtained from the operation of a nuclear reactor.

Nuclear reactor

A device in which nuclear fission can be sustained in a self-supporting chain reaction involving neutrons. In thermal reactors, fission is brought about by thermal neutrons.

Nuclear weapon

Explosive device deriving its power from fission or fusion of nuclei or from both.

Nucleus (of atom)

The core of an atom, occupying little of the volume, containing most of the mass, and bearing positive electric charge.

Nucleus (of cell)

The central part of a cell containing chromosomes and the genetic information bound in DNA.

Nuclide

A species of atom distinguished by its particular number of protons and number of neutrons.

Oocyte

The developing female gamete before maturation and release.

Organogenesis

The process of formation of specific organs in a plant or animal involving morphogenesis and differentiation.

Organometallic

An organic compound that contains a metal or metalloid element bonded directly to carbon.

Oxidation number

The number of electrons that must be added to a positive ion, or removed from a negative ion, to produce a neutral atom. Thus, for example, for vanadium in an oxidation state of +5, five electrons must be added to produce neutral vanadium.

Pelagic biota

Aquatic organisms living in the water column of a body of water, rather than along the shore or in the bottom sediments.

Photon

A quantum of electromagnetic radiation.

Photosynthesis

The formation of carbohydrates from carbon dioxide and a source of hydrogen (e.g. water) in the chlorophyll-containing tissues of plants exposed to light.

Positron

A positively charged beta$^+$ particle. Positrons rapidly interact with negatively charged electrons, releasing two gamma ray photons.

Pressurised water reactor (PWR)

A thermal reactor using water as both a moderator and coolant. Uses enriched uranium oxide fuel.

Primordial radionuclides

Radionuclides left over from the creation of the universe. They necessarily have very long half-lives, e.g. uranium-238 and thorium-232.

Progeny

Atomic nuclei produced from the radioactive decay of parent nuclei. Same as ëdaughtersí.

Proton

A fundamental nuclear particle with mass of 1.672614 x 10^{-27} kg and positive electric charge of 1. The proton is in effect a hydrogen nucleus.

Radiation

The emission and propagation of energy through space or through a material medium in the form of waves. The term may be extended to include streams of sub-atomic particles such as alpha and beta particles as well as electromagnetic radiation. Frequently used for ionising radiation, except when it is necessary to avoid confusion with non-ionising radiation.

Radiation weighting factor (w_r)

w_r values (radiation weighting factors) represent the relative biological effectiveness of the different radiation types, relative to X- or gamma rays, in producing endpoints of ecological significance.

Radioactive

The term used to describe an element that undergoes radioactive decay.

Radioactive half-life

The time taken for half of the atoms of a radioactive element to decay. Each radioisotope has a unique half-life. The half-life is a constant which is unaffected by any physical conditions such as temperature or pressure. Symbol $T^{1}/_{2}$.

Radioactive waste

Useless material containing radionuclides. Frequently categorised in the nuclear power industry according to activity and other criteria, as low level, intermediate level, and high level waste.

Radiobiology

The study of the effects of ionising radiation on living things.

Radiogenic

A term applied to radionuclides that arise from the decay of other radionuclides.

Radiological protection

The science and practice of limiting the harm to human beings from radiation.

Radionuclide

An unstable nuclide that emits ionising radiation.

Regulatory body

An authority or a system of authorities designated by the government of a state as having legal authority for conducting the regulatory process, including issuing authorisations and thereby regulating nuclear processes, radiation, radioactive waste and transport safety.

Relative Biological Effectiveness (RBE)

A relative measure of the effectiveness of different radiation types at inducing a specified health effect, expressed as the inverse ratio of the absorbed doses of two different radiation types that would produce the same degree of a defined biological endpoint.

Reprocessing

A process or operation, the purpose of which is to extract radioactive isotopes from spent fuel for further use.

Respiration

The process by which organic compounds of carbon in plant and animal tissue are broken down to carbon dioxide and water, at the same time releasing energy.

Risk

A measure of the probability and extent of harm.

Sievert

See effective dose.

Somatic cells

Soma, from the Greek meaning body. All body cells except the gametes and the cells from which the gametes develop.

Spent fuel

Nuclear fuel removed from a reactor following irradiation, which is no longer useable in its present form because of depletion of fissile material, poison build-up or radiation damage.

Spermatocytes

Cells of the male reproductive system.

Stem cell

A cell that upon division produces dissimilar daughters, one replacing the original stem cell, the other differentiating further (e.g. meristems of plants).

Stochastic effect

A radiation-induced health effect, the probability of occurrence of which is greater for a higher radiation dose and the severity of, which (if it occurs) is independent of dose.

Taxon (taxa)

A member of a formal classification of plants and animals according to their presumed natural relationships.

Telomere
The end of a chromosome.

Transitory exposure
Exposure that is too protracted to be described as acute exposure, but does not persist for many years, is sometimes described as transitory exposure.

Transuranic element
Elements of atomic number greater than that of uranium (atomic number 92). Examples are neptunium, plutonium, curium and americium

Wash-off
The removal of radionuclides from plant surfaces to the ground through the action of precipitation.

X-ray
A discrete quantity of electromagnetic energy without mass or charge, with less energy than gamma rays. They can be produced by the action of an electron beam on a metal target. They are emitted by some processes in radioactive decay.

CONTACTS:

THE ENVIRONMENT AGENCY HEAD OFFICE

Rio House, Waterside Drive, Aztec West, Almondsbury, Bristol BS32 4UD.
Tel: 01454 624 400 Fax: 01454 624 409

www.environment-agency.gov.uk
www.environment-agency.wales.gov.uk

ENVIRONMENT AGENCY REGIONAL OFFICES

ANGLIAN
Kingfisher House
Goldhay Way
Orton Goldhay
Peterborough PE2 5ZR
Tel: 01733 371 811
Fax: 01733 231 840

MIDLANDS
Sapphire East
550 Streetsbrook Road
Solihull B91 1QT
Tel: 0121 711 2324
Fax: 0121 711 5824

NORTH EAST
Rivers House
21 Park Square South
Leeds LS1 2QG
Tel: 0113 244 0191
Fax: 0113 246 1889

NORTH WEST
PO Box 12
Richard Fairclough House
Knutsford Road
Warrington WA4 1HG
Tel: 01925 653 999
Fax: 01925 415 961

SOUTHERN
Guildbourne House
Chatsworth Road
Worthing
West Sussex BN11 1LD
Tel: 01903 832 000
Fax: 01903 821 832

SOUTH WEST
Manley House
Kestrel Way
Exeter EX2 7LQ
Tel: 01392 444 000
Fax: 01392 444 238

THAMES
Kings Meadow House
Kings Meadow Road
Reading RG1 8DQ
Tel: 0118 953 5000
Fax: 0118 950 0388

WALES
Cambria House
29 Newport Road
Cardiff CF24 0TP
Tel: 029 2077 0088
Fax:029 2079 8555

ENVIRONMENT AGENCY
GENERAL ENQUIRY LINE
0845 9 333 111

ENVIRONMENT AGENCY
FLOODLINE
0845 988 1188

ENVIRONMENT AGENCY
EMERGENCY HOTLINE
0800 80 70 60

ENVIRONMENT AGENCY

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