Physical and **toxicological** characteristics of significant **radionuclides**

radionuclide	emission	physical half life[1]	specific activity (Bq/g)[2]	effective half life[3]	DPUI[4] (Sv)[1] inhalation 5 µm, workers (target organ)[5]	DPUI[4] (Sv)[1] ingestion 1 µm, public (target organ)[5]	ingestion factor[1] f_1 adult
^{3}H tritium (tritiated water)	beta	12.35 years	$3.57 \cdot 10^{14}$	12 days	$1.8 \cdot 10^{-11}$ (whole body)	$1.8 \cdot 10^{-11}$ (stomach)	1
^{7}Be beryllium	gamma	53.6 days	$1.29 \cdot 10^{16}$	41 days	$4.8 \cdot 10^{-11}$ (ET)[6]	$2.8 \cdot 10^{-11}$ (colon)	$5 \cdot 10^{-3}$
^{14}C carbon	beta	5,730 years	$1.65 \cdot 10^{11}$	40 days	$6.5 \cdot 10^{-12}$ (lung)	$5.8 \cdot 10^{-10}$ (stomach)	1
^{40}K potassium	beta + gamma	$1.2 \cdot 10^{9}$ years	$2.63 \cdot 10^{5}$		$2.4 \cdot 10^{-9}$ (colon)	$6.2 \cdot 10^{-9}$ (colon)	1
^{58}Co cobalt	beta + gamma	70.8 days	$1.18 \cdot 10^{15}$	8.4 days	$1.7 \cdot 10^{-9}$ (ET)[6]	$7.4 \cdot 10^{-10}$ (colon)	0.1
^{60}Co cobalt	beta + gamma	5.27 years	$4.18 \cdot 10^{13}$	9.5 days	$9 \cdot 10^{-9}$ (lung)	$3.4 \cdot 10^{-9}$ (colon)	0.1
^{79}Se selenium	beta	$1.1 \cdot 10^{6}$ years	$1.52 \cdot 10^{8}$		$3.1 \cdot 10^{-9}$ (kidney)	$2.9 \cdot 10^{-9}$ (kidney)	0.8
^{85}Kr krypton	beta + gamma	10.4 years	$1.5 \cdot 10^{13}$				
^{89}Sr strontium	beta	50.5 days	$1.07 \cdot 10^{15}$	50.3 days	$5.6 \cdot 10^{-9}$ (lung)	$2.6 \cdot 10^{-9}$ (colon)	0.3
^{90}Sr strontium	beta	29.12 years	$5.05 \cdot 10^{12}$	15.6 years	$7.8 \cdot 10^{-11}$ (lung)	$2.8 \cdot 10^{-8}$ (bone)	0.3
^{90}Y yttrium	beta + gamma	2.67 days	$2.01 \cdot 10^{16}$	64 h	$1.7 \cdot 10^{-9}$ (colon)	$2.7 \cdot 10^{-9}$ (colon)	10^{-4}
^{99}Tc technetium	beta + gamma	$2.14 \cdot 10^{5}$ years	$6.25 \cdot 10^{8}$	$\simeq$ 3 days	$4 \cdot 10^{-10}$	$6.4 \cdot 10^{-10}$	0.5
^{99m}Tc technetium	gamma	6.02 h	$1.95 \cdot 10^{17}$	6 h	$2.9 \cdot 10^{-11}$ (ET)[6]	$2.2 \cdot 10^{-11}$ (colon)	0.5
^{103}Ru ruthenium	beta + gamma	39.3 days	$1.19 \cdot 10^{15}$	2.38 days		$7.3 \cdot 10^{-10}$ (colon)	0.05
^{106}Ru ruthenium	beta + gamma	368.2 days	$1.24 \cdot 10^{14}$	2.4 days	$3.5 \cdot 10^{-8}$	$7 \cdot 10^{-9}$ (colon)	0.05
^{110m}Ag silver	beta + gamma	249.9 days	$1.75 \cdot 10^{14}$	4.8 days	$7.3 \cdot 10^{-9}$ (lung)	$2.8 \cdot 10^{-9}$ (colon)	0.05
^{124}Sb antimony	beta + gamma	60.2 days	$6.47 \cdot 10^{14}$	23 days	$4.7 \cdot 10^{-9}$ (lung)	$2.5 \cdot 10^{-9}$ (colon)	0.1
^{125}I iodine	gamma	60.14 days	$6.42 \cdot 10^{14}$		$1.4 \cdot 10^{-8}$ (thyroid)	$1.5 \cdot 10^{-8}$ (thyroid)	1
^{129}I iodine	beta + gamma	$1.57 \cdot 10^{7}$ years	$6.54 \cdot 10^{6}$		$5.1 \cdot 10^{-8}$ (thyroid)	$1.1 \cdot 10^{-7}$ (thyroid)	1
^{131}I iodine	beta + gamma	8.04 days	$4.6 \cdot 10^{15}$	7.6 days	$2 \cdot 10^{-8}$ (thyroid)	$2.2 \cdot 10^{-8}$ (thyroid)	1
^{132}I iodine HB	beta + gamma	2.3 h	$3.82 \cdot 10^{17}$	2 h	$3.1 \cdot 10^{-10}$ (thyroid)	$2.9 \cdot 10^{-10}$ (thyroid)	1
^{133}I iodine	beta + gamma	20.8 h	$4.19 \cdot 10^{16}$	0.87 day	$4 \cdot 10^{-9}$ (thyroid)	$4.3 \cdot 10^{-9}$ (thyroid)	1
^{133}Xe xenon	beta + gamma	5.24 days	$6.6 \cdot 10^{15}$				
^{134}Cs cæsium	beta + gamma	2.06 years	$4.78 \cdot 10^{13}$	65 days	$9.6 \cdot 10^{-9}$ (ET)[6]	$1.9 \cdot 10^{-8}$ (whole body)	1
^{135}Cs cæsium	beta + gamma	$2.3 \cdot 10^{6}$ years	$4.26 \cdot 10^{7}$		$3.1 \cdot 10^{-9}$	$2 \cdot 10^{-9}$	1
^{135}Xe xenon	beta + gamma	9.2 h	$9.33 \cdot 10^{16}$				
^{137}Cs cæsium	beta + gamma	30 years	$3.22 \cdot 10^{12}$	69.5 days	$6.7 \cdot 10^{-9}$ (ET)[6]	$1.3 \cdot 10^{-8}$ (colon)	1
^{144}Ce cerium	beta + gamma	284.3 days	$1.18 \cdot 10^{14}$	191 days	$2.9 \cdot 10^{-8}$ (lung)	$5.2 \cdot 10^{-9}$ (colon)	$5 \cdot 10^{-4}$
^{198}Au gold	beta + gamma	2.69 days	$9.07 \cdot 10^{15}$	2.6 days	$1.1 \cdot 10^{-9}$ (ET)[6]	$1 \cdot 10^{-9}$ (colon)	0.1
^{210}Pb lead	beta + gamma	22.3 years	$2.83 \cdot 10^{12}$	3.29 years*	$1.1 \cdot 10^{-6}$ (bone)	$6.9 \cdot 10^{-7}$ (bone)	0.2
^{212}Po polonium	alpha	138.38 days	$1.66 \cdot 10^{14}$	45 days	$2.2 \cdot 10^{-6}$ (lung)	$1.2 \cdot 10^{-6}$ (kidney)	0.5
^{222}Rn radon	alpha + gamma	3.82 days	$5.70 \cdot 10^{15}$				
^{224}Ra radium	alpha + gamma	3.66 days	$5.88 \cdot 10^{15}$	3.6 days	$2.4 \cdot 10^{-6}$ (lung)	$6.5 \cdot 10^{-8}$ (bone)	0.2
^{226}Ra radium	alpha + gamma	1,600 years	$3.64 \cdot 10^{10}$	$\simeq$ 15 years*	$2.2 \cdot 10^{-6}$ (lung)	$2.8 \cdot 10^{-7}$ (bone)	0.2
^{228}Th thorium	alpha + gamma	1.91 years	$3.03 \cdot 10^{13}$	1.89 year	$2.5 \cdot 10^{-5}$ (lung)	$7.2 \cdot 10^{-8}$ (bone)	$5 \cdot 10^{-4}$
^{228}Ra radium	beta + gamma	5.75 years	$1.01 \cdot 10^{13}$	5.7 years*	$1.7 \cdot 10^{-6}$ (lung)	$6.9 \cdot 10^{-7}$ (bone)	0.2
^{232}Th thorium	beta + gamma	$14.1 \cdot 10^{9}$ years	$4.04 \cdot 10^{3}$	> 100 years*	$5.9 \cdot 10^{-9}$ (lung)	$2.3 \cdot 10^{-7}$ (bone)	$5 \cdot 10^{-4}$
^{234}U uranium	alpha	246,000 years	$2.3 \cdot 10^{8}$	100 days	$6.8 \cdot 10^{-6}$ (ET)[6]	$4.9 \cdot 10^{-8}$ (bone)	0.02
^{235}U uranium	alpha + gamma	$7.04 \cdot 10^{8}$ years	$8 \cdot 10^{4}$	100 days	$6.1 \cdot 10^{-6}$ (ET)[6]	$4.7 \cdot 10^{-8}$ (bone)	0.02
^{238}U uranium	alpha + gamma	$4.47 \cdot 10^{9}$ years	$1.24 \cdot 10^{4}$	100 days	$5.7 \cdot 10^{-6}$ (ET)[6]	$4.5 \cdot 10^{-8}$ (bone)	0.02
^{237}Np neptunium	alpha + gamma	$5.4 \cdot 10^{6}$ years	$2.61 \cdot 10^{7}$	> 100 years*	$1.5 \cdot 10^{-5}$	$1.1 \cdot 10^{-7}$	$5 \cdot 10^{-4}$
^{238}Pu plutonium	alpha + gamma	87.7 years	$6.34 \cdot 10^{11}$	61.9 years*	$1.1 \cdot 10^{-5}$ (ET)[6]	$2.3 \cdot 10^{-7}$ (bone)	$5 \cdot 10^{-4}$
^{239}Pu plutonium	alpha + gamma	24,100 years	$2.3 \cdot 10^{9}$	> 100 years*	$2.3 \cdot 10^{-6}$ (bone)	$2.5 \cdot 10^{-7}$ (bone)	$5 \cdot 10^{-4}$
^{240}Pu plutonium	alpha + gamma	6,560 years	$8.41 \cdot 10^{9}$	> 100 years*	$8.3 \cdot 10^{-6}$ (bone)	$2.5 \cdot 10^{-7}$ (bone)	$5 \cdot 10^{-4}$
^{241}Am americium	alpha + gamma	432.7 years	$1.27 \cdot 10^{11}$	> 100 years*	$2.7 \cdot 10^{-5}$ (bone)	$2 \cdot 10^{-7}$ (bone)	$5 \cdot 10^{-4}$
^{241}Pu plutonium	alpha + beta + gamma	14.4 years	$3.81 \cdot 10^{12}$	12.33 years*	$8.4 \cdot 10^{-8}$ (bone)	$4.8 \cdot 10^{-9}$ (bone)	$5 \cdot 10^{-4}$
^{243}Am americium	alpha + gamma	7,370 years	$7.39 \cdot 10^{9}$	> 100 years*	$2.7 \cdot 10^{-5}$ (bone)	$2 \cdot 10^{-7}$ (bone)	$5 \cdot 10^{-4}$

(1) Reference: CD ROM of **ICRP**, publications 68 and 72.

(2) $A_i = (N \times \ln 2) / (M_i \times T_{i1/2})$ where N = Avogadro number $6.023 \cdot 10^{23}$, M_i atomic weight, $T_{i1/2}$ **physical half life** in seconds.

(3) The *effective half life* is the time after which half the radionuclide intaken has disappeared from the human body; it therefore depends on both the *physical half life* and the *biological half life*, the time after which half the corresponding element (radioactive or stable) has been eliminated by biological clearance.
In practice the physical half life is accurately known. The biological half life (for which data derive from several sources) depends on the **biokinetics** of the element, with its fast and slow elimination components (due to long residence in retention organs). This is why the effective half life is often approximately estimated. However it indicates the average residence time in the body, which is often much shorter than the physical half life. The figures followed by * are for half lives corresponding to retention in the skeleton.

(4) **DPUI**: dose per unit intake.

(5) The target organs indicated are those resulting from the **intake** of the **radionuclide** after transfer to the blood. When the **contamination** follows **inhalation**, the lung, the deposition organ, is also very often a target organ for the effects of both chemical and radiological toxicity. An element is more likely to be retained in the lung if it is an insoluble form.

(6) ET: extra-thoracic.

Physical and **toxicological** characteristics of significant **radionuclides**

radionuclide	body distribution target organs*	type of toxicity
^{3}**H** tritium	whole body	Bone marrow toxicity at very high dose (> TBq). No carcinogenic effect demonstrated in man.
^{7}**Be** beryllium	whole body, bone	Chemical toxicity by inhalation (pulmonary berylliosis), immuno-allergic reaction. RfD[7]: 0.002 mg/kg/day.
^{14}**C** carbon	whole body	No known toxicity, even at high doses, in mammals.
^{40}**K** potassium	whole body	No toxicity.
^{58}**Co** cobalt ^{60}**Co** cobalt	liver, bone, kidney, GIT[8]	Essential element. Chemical toxicity: heart, liver.
^{79}**Se** selenium	whole body, kidney, liver	Essential element. Chemical toxicity: clinical seleniosis (nails, skin, sensory disorders, depressed hæmoglobin). RfD[7]: 0.005 mg/kg/day.
^{85}**Kr** krypton	whole body	
^{89}**Sr** strontium ^{90}**Sr** strontium	bone	Chemical toxicity: rickets. RfD[7]: 0.6 mg/kg/day. Radiological toxicity: experimentally, at high doses, medullar hyperplasia, osteosarcoma, leukemia (~ 5 Sv).
^{90}**Y** yttrium	GIT[8]	
^{99}**Tc** technetium ^{99m}**Tc** technetium	whole body, thyroid, salivary glands, liver, GIT[8]	Experimentally, chemical toxicity of technetium: functional and histological modifications of the thyroid. **Lethal dose 50**: 13 mg/kg. For technetium 99, chemical toxicity > radiological toxicity.
^{103}**Ru** ruthenium ^{106}**Ru** ruthenium	whole body, GIT[8]	Chemical toxicity? (irritant vapour). Radiological toxicity: carcinogenic at high doses.
^{110m}**Ag** silver	whole body, liver, GIT[8]	Chemical toxicity: argyria (skin coloration). RfD[7]: 0.005 mg/kg/day.
^{124}**Sb** antimony	bone, liver	Experimentally, reduced life span, damage to skeleton.
^{125}**I** iodine ^{129}**I** iodine ^{131}**I** iodine ^{132}**I** iodine HB ^{133}**I** iodine	thyroid	Stable iodine deficiency causes hypothyroidism. At doses above 100 mGy in children, radioactive iodine can increase thyroid cancer risk. At all ages at doses above ~10 Gy, risk of permanent radio-induced hypothyroidism.
^{133}**Xe** xenon	whole body	
^{134}**Cs** cæsium ^{135}**Cs** cæsium	whole body, artery walls, adrenals	Cæsium-134: no observation in man. No known toxicity for cæsium-135.
^{135}**Xe** xenon	whole body	
^{137}**Cs** cæsium	whole body, artery walls, adrenals	Radiological toxicity of cæsium-137: at high doses (> 4.5 Gy), induces acute radiation syndrome with medullar aplasia. Experimentally, sarcomas observed (dose of a few Gy).
^{144}**Ce** cerium	liver, bone, GIT[8]	No observation in man. Experimentally, at doses > 5 Gy: acute effects, cancers (lung, bone, liver).
^{198}**Au** gold	kidney, GIT[8]	
^{210}**Pb** lead	bone, liver, kidney	Chemical toxicity: neurobehavioural development problems in children, enzyme modifications.
^{212}**Po** polonium	liver, kidney	
^{222}**Rn** radon	lung	Gas, decay product of short half life alpha emitters which remain bound to dust particles in the lung. Lung cancer.
^{224}**Ra** radium ^{226}**Ra** radium	bone	Osteosarcoma.
^{228}**Th** thorium	bone	Known effects in man through the colloidal contrast agent Thorotrast®, trapped by certain liver cells: excess leukemia and liver cancers, dose and dose rate-dependent.
^{228}**Ra** radium	bone	Osteosarcoma.
^{232}**Th** thorium	bone	*Idem* thorium 228.
^{234}**U** uranium ^{235}**U** uranium ^{238}**U** uranium	bone, kidney	Chemical toxicity: nephrotoxic. RfD[7]: 0.003 mg/kg/day (soluble forms). Radiological toxicity for isotopes 232 and 233. Caution: in the lung the carcinogenic action is multiple: dust accumulation, joint exposure to Rn and its decay products, external radiation, etc.
^{237}**Np** neptunium	bone, kidney, liver	No observation in man. Chemically and radiologically genotoxic. Experimentally, chemical toxicity for doses > mg/kg (dose lethal in a few days for doses > 10 mg/kg), liver damage, fibrosis (kidney, lung); carcinogenic (sarcomas) by radiological and chemical toxicity.
^{238}**Pu** plutonium ^{239}**Pu** plutonium ^{240}**Pu** plutonium	bone, kidney, liver, gonads	Radiological toxicity, target organs: lung (by inhalation), skeleton and liver (after systemic intake).
^{241}**Am** americium	bone, kidney, liver, gonads	Experimentally, at high doses, bone and liver cancers.
^{241}**Pu** plutonium	bone, kidney, liver, gonads	*Idem* plutonium 238, 239 and 240.
^{243}**Am** americium	bone, kidney, liver, gonads	*Idem* americium 241.

(7) RfD: reference dose, corresponding in chemical toxicology to the daily admissible dose without toxic effect. The values indicated are those retained by the **EPA**.
(8) GIT: gastro-intestinal tract.

A Natural and artificial radioactivity

Everything on the earth's surface has always been exposed to the action of ionising radiation from natural sources. Natural radiation, which accounts for 85.5% of total radioactivity (natural plus artificial), is made up of 71% telluric radiation and about 14.5% cosmic radiation. The radionuclides formed by the interaction of **cosmic rays** arriving from stars, and especially the Sun, with the nuclei of elements present in the atmosphere (oxygen and nitrogen) are, in decreasing order of dose (Box F, *From rays to dose*) received by the population, carbon-14, beryllium-7, sodium-22 and tritium (hydrogen-3). The last two are responsible for only very low doses.

Carbon-14, with a half life of **5,730 years**, is found in the human body. Its activity per unit mass of carbon has varied over time: it has diminished as carbon dioxide emissions from the combustion of fossil fuels have risen, then was increased by atmospheric nuclear weapon tests.

Beryllium-7, with a half life of **53.6 days**, falls onto the leaf surfaces of plants and enters the body by ingestion (Box B, *Human exposure routes*). About 50 Bq (becquerels) per person per year of beryllium-7 are ingested.

The main or **"primordial" radionuclides** are potassium-40, uranium-238 and thorium-232. Along with their radioactive decay products, these elements are present in rocks and soil and are therefore found in many building materials. Their concentrations are generally very low, but vary according to the nature of the mineral. The gamma radiation emitted by these radionuclides forms the **telluric radiation**, which is responsible for the external exposure of the body. The primordial radionuclides and many of their long-lived descendants are also found in trace amounts in drinking water and plants: this results in an internal exposure by ingestion, plus an additional low exposure by inhalation of airborne suspended dust particles.

Potassium-40 is a beta and gamma emitter with a half life of **1.2 thousand million years**, and has no radioactive descendants. This radioactive isotope makes up 0.0118% of all natural potassium, and enters the body by ingestion. The mass of natural potassium in the human body is independent of the quantity ingested.

Uranium-238 is an alpha emitter with a half life of **4.47 thousand million years**. It has thirteen main alpha-, beta- and gamma-emitting radioactive descendants, including **radon-222** (**3.82 days**) and **uranium-234** (**0.246 million years**). Uranium-238 and its two descendants **thorium-234** (**24.1 days**) and **protactinium-234m**(1) (**1.18 min**), and **uranium-234** are essentially incorporated by ingestion and are mainly concentrated in the bones and kidneys.

Thorium-230, derived from uranium-234, is an alpha emitter with a period of **80,000 years**. It is an osteotrope, but enters the body mainly by the pulmonary route (inhalation). **Radium-226**, a descendant of thorium-230, is an alpha emitter with a half life of **1,600 years**. It is also an osteotrope and enters the body mainly *via* food. Another osteotrope, **lead-210** (**22.3 years**), is incorporated by inhalation though mostly by ingestion.

Thorium-232 is an alpha emitter with a half life of **14.1 thousand million years**. It possesses ten main alpha-, beta- and gamma-emitting radioactive descendants including **radon-220** (**55 s**). Thorium-232 enters the body mainly by inhalation. **Radium-228**, a direct descendant of thorium-232, is a beta-emitter with a half life of **5.75 years**. It enters the body mainly in food.

Radon, a gaseous radioactive descendant of uranium-238 and thorium-232, emanates from the soil and building materials, and along with its short-lived alpha-emitting descendants constitutes a source of internal exposure through inhalation. Radon is the most abundant source of natural radiation (about 40% of total radioactivity).

The human body contains nearly 4,500 Bq of potassium-40, 3,700 Bq of carbon-14 and 13 Bq of radium-226 essentially imported in food.

Natural radiation is supplemented by an anthropic component, resulting from the medical applications of ionising radiation and to a lesser extent from the nuclear industry. It accounts for about 14.5% of the total radioactivity worldwide, but much more in the developed countries. In the medical field (more than 1 mSv/year on average in France), irradiation by external sources predominates: radiodiagnosis (X-rays) and radiotherapy, long based on cæsium-137 and cobalt-60 sources, but now more and more often using linear accelerators. Irradiation by internal routes (curietherapy with iridium-192) has more specialised indications (cervical cancer, for example). The metabolic and physicochemical properties of some twenty radionuclides are put to use for **medical activities** and in **biological research**. The medical applications comprise radiodiagnostics (scintigraphy and radio-

(1) m for metastable. A nuclide is said metastable when a transition delay exists between the excited state of the atom and the stable one.

immunology), and treatment, including thyroid disorders using iodine-131, radioimmunotherapy in certain blood diseases (phosphorus-32) and the treatment of bone metastasis with strontium-89 or radiolabelled phosphonates alongside other uses of radiopharmaceuticals. Among the most widely used radionuclides are: **technetium-99m** (half life **6.02 hours**) and **thallium-201** (half life **3.04 days**) (scintigraphy), **iodine-131** (half life **8.04 days**) (treatment of hyperthyroidism), **iodine-125** (half life **60.14 days**) (radioimmunology), **cobalt-60** (half life **5.27 years**) (radiotherapy), and **iridium-192** (half life **73.82 days**) (curietherapy). The average contribution of radiological examinations to total radioactivity amounts to 14.2%.

The **early atmospheric nuclear weapon tests** scattered fallout over the whole of the earth's surface and caused the exposure of populations and the contamination of the food chain by a certain number of radionuclides, most of which, given their short radioactive half lives, have now vanished. There remain **cæsium-137** (**30 years**), **strontium-90** (**29.12 years**), some **krypton-85** (**10.4 years**) and **tritium** (**12.35 years**), and the isotopes of **plutonium** (half lives **87.7 years** to **24,100 years**). Currently, the doses corresponding to the fallout from these tests are essentially attributable to fission products (cæsium-137) and to carbon-14, rather than activation products and plutonium.

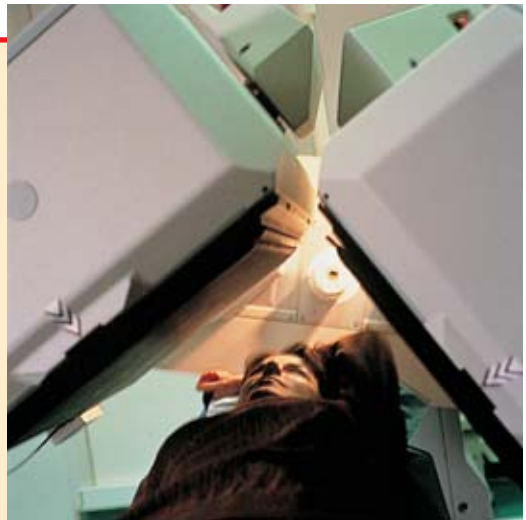
In the **Chernobyl accident** (Ukraine), which occurred in 1986, the total radioactivity dispersed into the atmosphere was of the order of 12 milliard milliard (10^{18}) becquerels over a period of 10 days. Three categories of radionuclides were disseminated. The first consisted of volatile fission products such as **iodine-131**, **iodine-133** (**20.8 hours**), **cæsium-134** (**2.06 years**), **cæsium-137**, **tellurium-132** (**3.26 days**). The second was composed of solid fission products and actinides released in much smaller amounts, in particular the strontium isotopes ^{89}**Sr** (half life **50.5 days**) and ^{90}**Sr**, the ruthenium isotopes ^{103}**Ru** (half life **39.3 days**) and ^{106}**Ru** (half life **368.2 days**), and **plutonium-239** (**24,100 years**). The third category was rare gases which although they represented most of the activity released, were rapidly diluted in the atmosphere. They were mainly **xenon-133** (**5.24 days**) and **krypton-85**.

The contributions of the early atmospheric nuclear weapon tests and the Chernobyl accident to the total radioactivity are roughly 0.2% (0.005 mSv) and 0.07% (0.002 mSv) respectively.

The whole of the **nuclear-powered electricity production** cycle represents only about 0.007% of total radioactivity. Almost all the radionuclides remain confined inside the nuclear reactors and the fuel cycle plants. In a nuclear reactor, the reactions that take place inside the fuel yield transuranics. **Uranium-238**, which is non-fissile, can capture neutrons to give in particular plutonium isotopes ^{239}**Pu**, ^{240}**Pu** (half life **6,560 years**) and ^{241}**Pu** (half life **14.4 years**), and **americium-241** (**432.7 years**). The main fission products generated by the fission of **uranium-235** (**704 million years**) and **plutonium-239** are **iodine-131**, **cæsium-134**, **cæsium-137**, **strontium-90** and **selenium-79** (**1.1 million years**).

The main radionuclides present in releases, which are performed in a very strict regulatory framework are, in liquid release, **tritium**, **cobalt-58** (**70.8 days**), **cobalt-60**, **iodine-131**, **cæsium-134**, **cæsium-137** and **silver-110m** (**249.9 days**). In gaseous releases **carbon-14** is the most abundant radionuclide, emitted most often as carbon dioxide. In all the reactors in the world, the total production of radiocarbon dioxide amounts to one tenth of the annual production formed naturally by cosmic radiation.

In addition, certain radionuclides related to the nuclear industry exhibit chemical toxicity (Box D, *Radiological and chemical toxicity*).



Laurence Médard/CEA

Classical scintigraphy performed at the Frédéric-Joliot Hospital Service (SHFJ). The gamma-ray camera is used for functional imaging of an organ after administration, usually by the intravenous route, of a radioactive drug (radiopharmaceutical) to the patient. The radionuclides used are specific to the organ being studied: for example, technetium-99m for the kidneys and bones, thallium-201 for the myocardium. The injected radiopharmaceutical emits gamma photons, which are captured by two planar detectors placed at 180° or 45° according to the examination.

B Human exposure routes

Human **exposure**, i.e., the effect on the body of a chemical, physical or radiological agent (irrespective of whether there is actual contact), can be external or internal. In the case of **ionising radiation**, exposure results in an energy input to all or part of the body. There can be direct **external irradiation** when the subject is in the path of radiation emitted by a radioactive source located outside the body. The person can be irradiated directly or after reflection off nearby surfaces.

The irradiation can be **acute** or **chronic**.

The term **contamination** is used to designate the deposition of matter (here **radioactive**) on structures, surfaces, objects or, as here, a living organism. Radiological contamination, attributable to the presence of **radionuclides**, can occur by the **external** route from the receptor medium (air, water) and vector media (soils, sediments, plant cover, materials) by contact with skin and hair (cutaneous contamination), or by the **internal** route when the radionuclides are **intaken**, by **inhalation** (gas, particles) from the atmosphere, by **ingestion**, mainly from foods and beverages (water, milk), or by penetration (injury, burns or diffusion through the skin). The term **intoxication** is used when the toxicity in question is essentially chemical.

In the case of **internal contamination**, the dose delivered to the body over time (called the **committed dose**) is calculated for 50 years in adults, and until age 70 years in children. The parameters taken into account for the calculation are: the nature and the intaken quantity of the radionuclide (RN), its chemical form, its **effective half life**[1] in the body (combination of **physical** and **biological half lives**), the type of **radiation**, the mode of exposure (inhalation, ingestion, injury, transcutaneous), the distribution in the body (deposition in target organs or even distribution), the radiosensitivity of the tissues and the age of the contaminated subject.

Lastly, the **radiotoxicity** is the toxicity due to the ionising radiation emitted by the inhaled or ingested radionuclide. The misleading variable called **potential radiotoxicity** is a *radiotoxic inventory* that is difficult to evaluate and made imprecise by many uncertainties.

(1) The effective half life (Te) is calculated from the physical half life (Tp) and the biological half life (Tb) by $1 / Te = 1 / Tp + 1 / Tb$.

F From rays to dose

Radioactivity is a process by which certain naturally-occurring or artificial **nuclides** (in particular those created by **fission**, the splitting of a heavy nucleus into two smaller ones) undergo spontaneous **decay**, with a release of energy, generally resulting in the formation of new nuclides. Termed **radionuclides** for this reason, they are unstable owing to the number of nucleons they contain (protons and neutrons) or their energy state. This decay process is accompanied by the emission of one or more types of **radiation**, ionising or non-ionising, and (or) particles. **Ionising radiation** is electromagnetic or corpuscular radiation that has sufficient energy to ionise certain atoms of the matter in its path by stripping electrons from them. This process can be *direct* (the case with alpha particles) or *indirect* (gamma rays and neutrons).

Alpha radiation, consisting of helium-4 nuclei (two protons and two neutrons), has low penetrating power and is stopped by a sheet of paper or the outermost layers of the skin. Its path in biological tissues is no longer than a few tens of micrometres. This radiation is therefore strongly ionising, i.e., it easily strips electrons from the atoms in the matter it travels through, because the particles shed all their energy over a short distance. For this reason, the hazard due to radionuclides that are **alpha emitters** is **internal exposure**.

Beta radiation, made up of electrons (beta minus radioactivity) or positrons (beta plus radioactivity), has moderate penetrating power. The particles emitted by **beta emitters** are stopped by a few metres of air, aluminium foil, or a few millimetres of biological tissue. They can therefore penetrate the outer layers of the skin.

Gamma radiation composed of high energy photons, which are weakly ionising but have high penetrating power (more than the **X-ray** photons used in radiodiagnosis), can travel through hundreds of meters of air. Thick shielding of concrete or lead is necessary to protect persons.

The interaction of **neutron radiation** is random, and so it is stopped only by a considerable thickness of concrete, water or paraffin wax. As it is electrically neutral, a neutron is stopped in air by the nuclei of light elements, the mass of which is close to that of the neutron.

• The quantity of energy delivered by radiation is the **dose**, which is evaluated in different ways, according to whether it takes into account the quantity of energy absorbed, its rate of delivery, or its biological effects.

• The **absorbed dose** is the quantity of energy absorbed at a point per unit mass of matter (inert or living), according to the definition of the International Commission on Radiation Units and Measurements (**ICRU**). It is expressed in **grays** (Gy): 1 gray is equal to an absorbed energy of 1 joule per kilogramme of matter. The *organ absorbed dose* is obtained by averaging the doses absorbed at different points according to the definition of the International Commission on Radiological Protection (**ICRP**).

• The **dose rate**, dose divided by time, measures the intensity of the irradiation (energy absorbed by the matter per unit mass and per unit time). The legal unit is the gray per second (Gy/s), but the gray per minute (Gy/min) is commonly used. Also, radiation has a higher **relative biological effectiveness (RBE)** if the effects produced by the same dose are greater or when the dose necessary to produce a given effect is lower.

• The **dose equivalent** is equal to the dose absorbed in a tissue or organ multiplied by a **weighting factor**, which differs according to the nature of the radiation energy, and which ranges from 1 to 20. Alpha radiation is considered to be 20 times more harmful than gamma radiation in terms of its biological efficiency in producing random (or **stochastic**) effects. The equivalent dose is expressed in sieverts (Sv).

• The **effective dose** is a quantity introduced to try to evaluate harm

Foulon/CEA

Technicians operating remote handling equipment on a line at the Atalante facility at CEA Marcoule. The shielding of the lines stops radiation. The operators wear personal dosimeters to monitor the efficacy of the protection.

in terms of whole-body stochastic effects. It is the sum of *equivalent doses* received by the different organs and tissues of an individual, weighted by a factor specific to each of them (weighting factors) according to its specific sensitivity. It makes it possible to sum doses from different sources, and both external and internal radiation. For internal exposure situations (**inhalation**, **ingestion**), the effective dose is calculated on the basis of the number of **becquerels** incorporated of a given radionuclide (**DPUI**, **dose per unit intake**). It is expressed in sieverts (Sv).

• The **committed dose**, as a result of internal exposure, is the cumulated dose received in fifty years (for workers and adults) or until age 70 (for those aged below 20) after the year of **incorporation** of the radionuclide, unless it has disappeared by physical shedding or biological elimination.

• The **collective dose** is the dose received by a population, defined as the product of the number of individuals (e.g., those working in a nuclear plant, where it is a useful parameter in the optimisation and application of the ALARA system) and the average equivalent or effective dose received by that population, or as the sum of the individual effective doses received. It is expressed in man-sieverts (man.Sv). It should be used only for groups that are relatively homogeneous as regards the nature of their exposure.

D Radiological and chemical toxicity

The chemical toxics linked to the nuclear industry include **uranium** (U), **cobalt** (Co), **boron** (B), used for its neutron-absorbing properties in the heat-exchange fluids of nuclear power plants, **beryllium** (Be), used to slow neutrons, and **cadmium** (Cd), used to capture them. Boron is essential for the growth of plants. Cadmium, like lead (Pb), produces toxic effects on the central nervous system. When the toxicity of an element can be both radiological and chemical, for example that of plutonium (Pu), uranium, neptunium, technetium or cobalt, it is necessary whenever possible to determine what toxic effects are radiological, what are chemical, and what can be either radiological or chemical (see *Limits of the comparison between radiological and chemical hazards*).

For **radioactive** elements with long physical **half lives**, the chemical toxicity is a much greater hazard than the radiological toxicity, as exemplified by rubidium (Rb) and natural uranium. Thus the chemical toxicity of uranium, which is more important than its radiological toxicity, has led the French regulators to set the **ingested** and **inhaled** mass limits for uranium in chemical compounds at 150 mg and 2.5 mg per day respectively, regardless of the **isotopic** composition of the element.

Certain metals or **metalloids** that are non-toxic at low concentrations can become toxic at high concentrations or in their radioactive form. This is the case for cobalt, which can be **genotoxic**, selenium (Se) (naturally incorporated in **proteins** or **RNA**), technetium (Tc) and iodine (I).

Cyrille Dupont/CEA

Two-dimensional gel electrophoresis image analysis carried out in the course of nuclear toxicology work at CEA Marcoule Centre in the Rhone Valley.