I. FROM SOURCE TO MAN

Starting from the source, the first objective of research in nuclear toxicology is to be able to describe, ever more accurately, the mechanisms of transfer of toxic agents – radionuclides or heavy metals and metalloids – between the external environment and living organisms, from bacteria to man, from the geosphere to the biosphere. In addition to direct external irradiation, human exposure can come from the air, water or food *via* different entry routes – inhalation, ingestion and sometimes injury.

This research field is a particularly multidisciplinary one, mobilising expertise in chemistry, physical chemistry, biochemistry, biology and ecotoxicology. The specialists in all these areas, for example in the study of biogeochemical cycles implicating organisms in its environment, have also to be proficient in modelling and computation to understand and translate the mechanisms involved.

The study of transfer from the soil *to plants* is obviously a most important topic because this transfer can be the first step in the contamination of the human food chain by pollutants. The study of transfer *to animals* has a dual utility: first, animals are sources of derived products that are consumed by man (milk, meat, eggs, etc.), and second, their study provides models of biological mechanisms and metabolism that give insight on their human equivalents.

When studying these transfers, it is essential to be able to track the fate of the toxics in question and identify the different successive forms they may adopt in their journey from source to man. To determine this *speciation* of the toxics, in both physicochemical and biological terms, theoretical tools just as analytical methods and equipment have made great advances in the last few years.

Human beings have always been subjected to natural background radiation. This exposure is now supplemented by radiation due to human activities, predominantly in medicine, and to a much lesser degree from other civil or military nuclear energy applications. Radionuclides, which are present in all the compartments of the human environment, can also reach human beings *via* the air, water or food. The study of the routes of absorption by the human body is thus necessary in addition to that of their transport in both plants and animals, in research on the control of radiation exposure.

The **exposure routes**

Jeremy Woodhouse/PhotoDisc

Radionuclides, whether of natural or artificial origin, are present in all the compartments of the environment, and are dispersed by the general circulation of the atmosphere and hydrosphere. Radionuclides emitted in gaseous form or as very fine solid or liquid particles are distributed throughout the atmosphere before settling on the ground and on plants.

Air, water and food

Radionuclides in all the compartments of the environment

Some 85% of the background **radiation** that human beings are subjected to is **natural telluric radioactivity** and **cosmic rays**. This exposure is now supplemented by an **anthropic contribution**, resulting from medical applications of **ionising radiation** and the civil and military nuclear industries (Box A, ***Natural and artificial radioactivity***; Tables 1 and 2).

Nearly 36% of **exposure** to natural radiation occurs **externally**, when the source of exposure is outside the body. **Internal exposure** (64% of the natural dose) implies the transfer of **radionuclides** to humans, their absorption and their **uptake** (Box B, ***Human exposure routes***). These radionuclides derive mainly from interactions between man and the environment, *via* the **compartments** formed by the air, water and food. Besides elements such as carbon and potassium, which are vital, and which therefore contribute an unavoidable radioactivity in living organisms (a person weighing 70 kg contains about 4,500 **becquerels** (**Bq**) of potassium-40 and 3,700 Bq of carbon-14), food supplies many other natural radionuclides, in particular uranium and thorium, and their descendants (Tables 3 and 4).

The air we breathe also contains **radon** gas, a decay product of uranium and radium, in particular in granite regions, which is inhaled along with wind-borne mineral particles that naturally contain uranium, thorium and potassium-40. For example, in France, the average concentration of radon in dwellings is

Table 1.
World-wide annual **dose** of ionising radiation of natural and artificial origin estimated for the year 2000 (**UNSCEAR** report 2000).

source of radiation	average annual dose per inhabitant (mSv)	approximate share (%)
natural background (cosmic and telluric radiation)	2.4*	85.5
medical examinations	0.4**	14.2
fallout from old atmospheric nuclear tests	0.005	0.2
accident at Chernobyl (1986)	0.002 (northern hemisphere)	0.07
nuclear power production	0.0002	0.007

* variations in natural exposure are wide, between 1 and 100 mSv/year.

** in industrial countries, medical exposure, due essentially to doses received during diagnostic examinations, exceeds 1 mSv/year on average.

Table 2.
Origin and relative amounts of world-wide average annual **doses** of radiation received by humans from natural radiation sources (**UNSCEAR** report 2000).

cosmic radiation	telluric radiation	
0.4 mSv/year (17%)	2.0 mSv/year (83%)	24% by external exposure (soil, rock, etc.)
		63% by inhalation (uranium- and thorium-containing particles, radon, etc.)
		13% by ingestion (uranium- and thorium-containing particles, potassium-40, etc.)

radionuclide	activity in the air (mBq/m^3)
tritium (^{3}H)	1.4
beryllium-7 (^{7}Be)	12.5
carbon-14 (^{14}C)	56.3
uranium-238 (^{238}U)	0.001
uranium-235 (^{235}U)	0.00005
uranium-234 (^{234}U)	0.001
lead-210 (^{210}Pb)	0.5
thorium-232 (^{232}Th)	0.0005
thorium-230 (^{230}Th)	0.0005
thorium-228 (^{228}Th)	0.001
radium-228 (^{228}Ra)	0.001
radium-226 (^{226}Ra)	0.001

Table 3.
World-wide concentration (**activity**) of natural radionuclides in the air (**UNSCEAR** report 2000).

estimated at 90 Bq/m^3 of air, but can fluctuate widely according to the region and from one dwelling to other from 1 to about 5,000 Bq/m^3. These emanations of radon make up about one half of the annual dose of telluric origin.

Different sources of radioactivity for various types of transfer

The radionuclides are ubiquitous in all the compartments of the environment. Regardless of their physical form, they are carried by the movements of the air and water around the planet in the form of gases and **aerosols** in the general circulation of the atmosphere, and as dissolved, particulate and **colloidal** species in the flow of ground water, rivers and the ocean circulation. This circulation tends to even out the distribution of radionuclides and dilutes them. However, radionuclides are also deposited from the atmosphere onto the ground and can precipitate and settle in the hydrosphere(1), and so accumulate locally.
Other sources add to the global distribution of radionuclides. They may be natural effects, such as a volcanic eruption, or the human technological use of radioactivity. All these anthropic activities are *isolated* sources that mark the environment most often locally. In general, scientists do not seek to model the transport of radionuclides in the environment except in cases that lie outside the natural domain. The radiation sources attributable to human activity are the subject of considerable research in physical modelling and mathematical simulation.

InterNetwork Media/PhotoDisc

Eruption of Mount St Helens, Washington State (USA). A volcanic eruption adds to the global amounts of radionuclides present in the environment.

(1) Hydrosphere: all the compartments on the earth that contain water (lakes, rivers, seas, oceans).

foods	uranium-238 (^{238}U)	radium-226 (^{226}Ra)	lead-210 (^{210}Pb)	thorium-232 (^{232}Th)
dairy produce	1	5	15	0.3
meat	2	15	60	1
green vegetables	20	50	80	15
fruit and vegetables	3	30	40	0.5
fish	30	100	200	10
drinking water (mBq/L)	1	0.5	5	0.05

These figures do not account for the extreme disparity of locally measured levels. For example, uranium-238 levels in drinking water can vary in Finland from 0.5 to 150,000 mBq/L. In France, they range from 4.4 to 930 mBq/L. (For comparison, the concentration of uranium-238 in sea water is 30 mBq/L). The level of radium-226 in French mineral water can range from 30 mBq/L to nearly 2,000 Bq/L according to its origin, depending, in particular, on the ground through which the water has been flowing.

Table 4.
World-wide average concentrations (**activities**) of radionuclides in food products (mBq/kg) (**UNSCEAR** report 2000).

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.

A (next)

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.

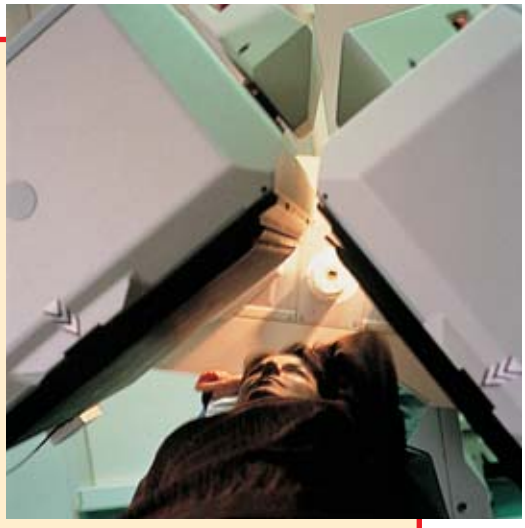
In the **Chernobyl accident** (Ukraine), which occurred in 1986, the total radioactivity dispersed into the atmosphere was of the order of 12 milliard milliard (10^{18}) becquerels over a period of 10 days. Three categories of radionuclides were disseminated. The first consisted of volatile fission products 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.

PhotoLink/PhotoDisc

Havasu falls, Arizona (USA). Water is an important carrier of radionuclides, which can circulate in different physicochemical forms. Their behaviour in solution is governed by numerous parameters.

The mechanisms of transfer by the air

The atmosphere is the primary medium through which gases and aerosols migrate. Released into the air from industrial flues and vents, radionuclides present in these physical forms are scattered under the combined influence of advection(2) by wind and turbulent dispersion(3). In addition, gas and particles undergo wet deposition (*via* rainfall) and dry deposition on the ground and on plants.

Specialists in fluid mechanics study atmospheric flow and the transport of particles and gases in the air using physical models and calculations. These have ranging levels of complexity depending on how accurate the result has to be and how rapidly it is needed.

The mechanisms of transfer by water

Water, the distribution of which is heterogeneous in soils and rocks, is an important transport vector because it is potentially quickly mobilised, unlike the soils and rocks that contain it.

The dispersion or re-concentration of radionuclides in water depends on numerous physical and chemical parameters that control their behaviour in solution and their interactions with solid phases. The permeability of the hydrogeological media, the composition of the water and the presence of colloids are the most relevant factors. The rate of migration of radionuclides is thus delayed relative to water. This delay, which vary according to the nature of the radionuclides, their physicochemical form and the medium in which they are contained, generates chemical and **isotopic** fractionation. The measure of this delay and fractionations provides insight into the mechanisms of transfer of radionuclides in the environment.

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(2) Advection: horizontal displacement of a mass of gas (air in the present case) (unlike convection, which is vertical).

(3) Turbulence: pattern of flow of a fluid in which random movements are superimposed on an average movement.

PhotoLink/PhotoDisc

Food supplies us with many vital elements, of which some have naturally-occurring radionuclides. An accidental release of radionuclides into the environment could contaminate the food chain, thereby forming a major source of human exposure.

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.