An element whether radioactive or not can occur in many physicochemical forms in the environment and in biological media that it may happen to pass through. From a chemical and biological point of view, speciation means determining what different species of this element are present. This is a key operation in the evaluation of the mobility, bioavailability and thereby the real human toxicity of the considered element.

Speciation in the environment and in biological media

A. Renaud - Cadam/CEA

Experimental CE/ICP-MS coupling used to determine the speciation of elements in the environment and in biological media. After sample loading the elements are separated by Capillary Electrophoresis (CE) and detected by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) where the plasma temperature reaches about 7,000 °C. This method allows to identify, characterise and quantify the different physicochemical forms of the elements at very low levels of concentration.

pH	U(VI) species	% transfer to plants
5	UO_2^{2+} (80%) (free form)	100
6	$UO_2(OH)^+$ (94%) (hydrolysed form)	20
8	carbonate complexes (100%) (carbonated form)	5

Table 1.
Influence of the physicochemical form (free, **hydrolysed** or carbonated) of uranium on its transfer to plants.
(G. Bernhard, INE/Rossendorf, NRC5 Conference, 1999).

Speciation, a basic approach in many areas

Determining the speciation of an element in a particular medium implies to identify, characterise and quantify the different physicochemical forms of that element. This involves defining the chemical form (**oxidation state**, charge, proportion and nature of the **complexed** forms) and sometimes the physical form (distribution among soluble, **colloidal** or particulate forms, and solid phases, modes of association and physical localisation) in which it occurs. According to the field, chemical or biological, there are two definitions of speciation. *Chemical speciation* which is static, describes the operational process of identification and quantification of a chemical species containing a particular element. *Biological speciation*, which is a more dynamic concept, concerns the conversion of one species into another through a dynamic reaction process.
Speciation is a key parameter that will determine the behaviour and the mobility of the elements in a medium, their **bioavailability** and so their toxicity. Knowledge of speciation is therefore an essential tool for understanding and interpreting the mechanisms involved in the reactivity of elements, and for scaling associated experiments (Table 1).
The concept of speciation in biological and environmental media is relevant, in particular, to many of the projects of the Nuclear Toxicology Programme (Box, *The CEA Programme*) and is also highly important in the different parts of the nuclear **fuel** cycle (reprocessing) and nuclear waste management.

The media of interest

In the nuclear toxicology context, questions arise such as: under which physicochemical form is an element present in trace amounts before **uptake**/**ingestion**/ transfer to a particular living organism? In what form will it occur in that organism? How will it be transported? Hence the media of interest will mainly be water and soils, which will be in contact with the **biosphere**, another medium in which the speciation will have to be determined. Table 2 gives the average compositions of some environmental and biological media of interest.

Measurement methods and instrumentation

Speciation can be determined essentially by two ways, either by calculating the distribution of chemical forms from thermodynamic stability constants that describe the chemical equilibria involved, or by direct or indirect analytical methods.

The calculation approach

This approach requires knowing the composition of the medium, in particular in terms of complexing agents, and the physicochemical equilibria involved along with the associated thermodynamic constants. This then enables us to calculate:
- in solution, *the solubility and distribution of the different complexed forms in the given medium*, the medium being completely defined by its composition, i.e., **pH**, **redox potential** (*Eh*), **ionic strength**, concentrations of **cations** and **anions** with identification of **ligands** or complexing agents (inorganic, organic and biological compounds);
- in a solid-solution system, considering the presence of colloids and particles, of solid substrates (mineral surfaces, biological interfaces, etc.), *the distribution of the element between liquid and solid phases*.

An example of the determination of cobalt speciation in a biological medium, given in Figure 1, shows the influence of the composition of the medium according to whether organic complexing agents such as citrates are taken into account. Figure 2 illustrates the speciation of uranium U(VI) in an environmental medium, in particular in the presence of naturally occurring organic materials (humic substances).
Speciation diagrams are usually generated with the aid of theoretical methods, for example **computation codes** (JCHESS, SCDatabase, etc.), developed by various organisations, which also make possible to allow for problems of **precipitation** or colloid formation and for redox potentials. One of the key prerequisites of this process, besides knowledge of the medium, is to have thermodynamic constants. If they

species	surface water pH = 6.5-8.5	blood pH = 7.4
Ca^{2+} (calcium ion)	$10^{-3.4}$ M	0.0014 M
K^+ (potassium ion)		$4.9 \cdot 10^{-4}$ M
Mg^{2+} (magnesium ion)	$10^{-3.8}$ M	$5.6 \cdot 10^{-4}$ M
Na^+ (sodium ion)	$10^{-3.6}$ M	0.09 M
Fe (iron)		0.3 µM
H_4SiO_4 (silicic acid)	$10^{-3.7}$ M	
Cl^- (chloride ion)	$10^{-3.7}$ M	0.09 M
PO_4^{2-} (phosphate ion)		0.0011 M
SO_4^{2-} (sulfate ion)		0.00033 M
HCO_3^- (bicarbonate ion)	0.001 M	
CO_3^{2-} (carbonate ion)		0.025 M
organic carbon *(including humic[1] substances)*	1-50 mg/L	
citrates ($C_6H_5O_7^{3-}$)		$1.6 \cdot 10^{-4}$ M
lactates ($C_3H_5O_3^-$)		$1.5 \cdot 10^{-3}$ M
oxalates ($C_2O_4^{2-}$)		9.2 µM
albumin		$6.3 \cdot 10^{-4}$ M
transferrin		$3.7 \cdot 10^{-5}$ M

(1) Humic substances are organic compounds present in the soil, sediments and water, derived from fermentable organic matter (of animal, plant or bacterial origin). They are composed mainly of humins, humic acids and fulvic acids.

Table 2.
Examples of average compositions (non-exhaustive), expressed in moles per litre (M) or in milligrammes per litre (mg/L), of environmental and biological media. (Laura Sigg, Werner Stumm, Philippe Behra, *Chimie des milieux aquatiques*, ed. Masson, 1994, for surface water).

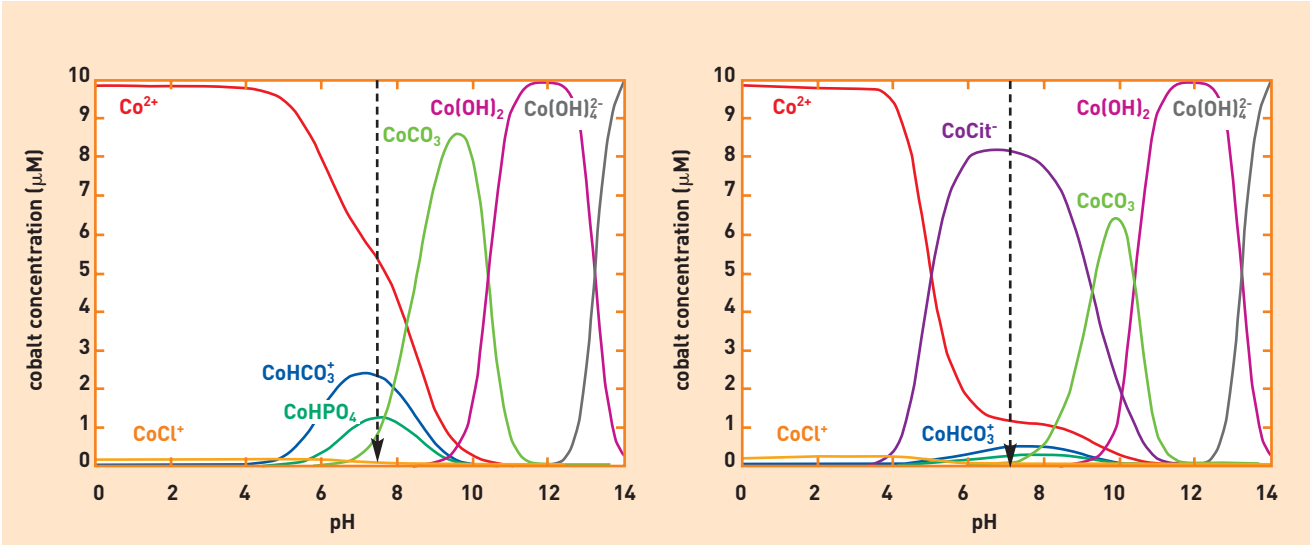


Figure 1. Determination of the speciation of cobalt at a concentration of 10 μM in blood without citrates (left) and with a 10^{-4} M solution of citrates (right). The composition of the medium is given in Table 2.

are available, it is essential to be sure of their robustness and their reliability through data compilation and critical analysis, as performed in the framework of international work conducted by the **OECD/NEA** for elements such as plutonium (Pu), americium (Am), neptunium (Np), uranium (U), technetium (Tc), etc., and to which French experts have contributed. If, on the other hand, the data are not available, then an approach by analogy is possible, based on analogies in chemical behaviour, such as, for example, between the **lanthanides** and **trivalent actinides**. However, data can be collected and measured using appropriate analytical methods or the same ones as used to determine speciation.

Figure 3 illustrates the use of Time-Resolved Laser Spectrofluorimetry (TRLS) to study the system formed by uranium (VI) and **transferrin** (the main actinide carrier **protein**). The fluorescence spectra of uranium in this biological medium are presented for different uranium (VI)/transferrin concentration ratios. The very high associated conditional thermodynamic constant ($\log K = 16$ in M^{-2}) shows a very high affinity of the uranyl ion (UO_2^{2+}) for transferrin, and is the first value recorded in the literature for this system.

The analytical approach

The determination of speciation *via* direct analytical methods has been developed owing to the continual advances in the performances of analytical tools. Given the complexity of the biological and environmental media, it is advisable first to study simple systems, a single ligand, for example, representative of the media of interest, supported by a facility offering an array of spectroscopic methods to gain access to complementary data and also to cross-check pre-existing information. After validation of the tools on these simple systems, application to complex media can be considered.

These methods can be split, non-exhaustively, into two main categories. *Direct* methods, such as those of laser spectrometry (fluorescence, photoacoustics, etc.) and mass spectrometry, allow to work directly on a sample. *Indirect* methods rely on the use of separative methods (dialysis, ultrafiltration, chromatography, electrophoresis,

Injection of a liquid sample into an Electrospray Mass Spectrometer (ES-MS) to determine the elements, ligands and complexes present in solution and detected in the gas phase. ES-MS, by its "gentle" mode of ionisation, gives direct access to the speciation in solution.

Laurence Médard/CEA

resins) and detection of one or several elements (atomic absorption, plasma torch with detection by Atomic Emission Spectroscopy (AES) or Mass Spectrometry (MS), radiochemical or electrochemical methods).
Below are some methods used and the information they can provide:

- *Nuclear Magnetic Resonance* (NMR) supplies information on the structure and stœchiometry(1) of complexes, and allows the determination of complexation constants;
- *Extended X-ray Absorption Fine Structure* (EXAFS) offers the means to study the chemical environment of an element and obtain data such as oxidation state, **co-ordination**, type, number and distances of neighbouring atoms;
- *Electrospray Mass Spectrometry* (ES-MS) gives the means to characterise and quantify chemical species. Using this method it is possible to gain *direct* access to the speciation and thereby measure complexation constants, and also to the **isotopy**;
- *Time-Resolved Laser Spectrofluorimetry* (TRLS) allows the characterisation of species and the determination of complexation constants and co-ordination numbers;
- *High Performance Liquid Chromatography* or *Capillary Electrophoresis* coupled with *Inductively Coupled Plasma Mass Spectrometry* (HPLC/ICP-MS) allows separation and speciation at very low concentrations, thanks to ICP-MS detection, and isotopy determination. Experimental CE/ICP-MS coupling has determined speciation at concentration levels as low as 10^{-12} M;
- *Radiochemical and chemical separations* provide the redox speciation of elements (for example, the distribution of oxidation states of plutonium in natural media such as oceans, lakes and rivers) at very low concentrations (down to 10^{-16} M). These methods mainly involve solvent extraction, co-precipitation and separation on resins.

The use of these different methods, in addition to the complementarity of the structural and chemical data obtained, also offers the possibility of working in a wide range of concentrations (0.1 to 10^{-12} M). Thus the availability of an array of methods allows to determine the speciation of an element, and in particular the stœchiometry and complexation constant(s) of the element considered with the

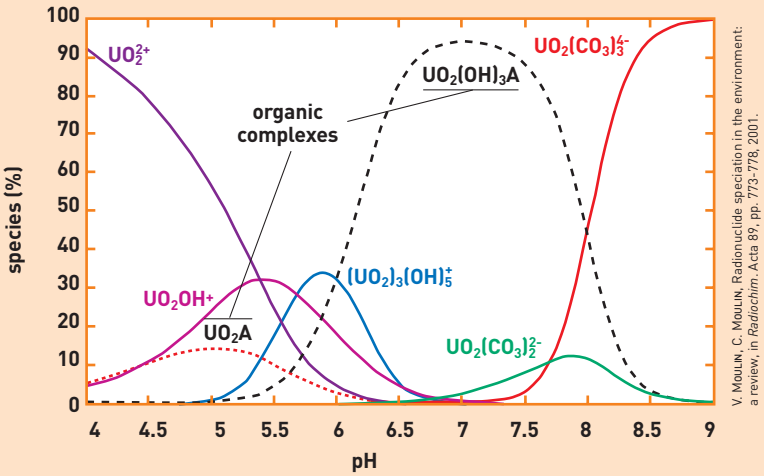


Figure 2.
Speciation of uranium (VI) in an environmental medium in the presence of naturally-occurring organic materials (humic substances A) in the following conditions: concentration of uranium [U] = 1 mg/L, concentration of humic substances [A] = 1 mg/L, non-complexing sodium perchlorate ($NaClO_4$) medium with ionic strength 0.1 M, carbon dioxide partial pressure (pCO_2) set at $10^{-3.5}$ atm.

The equilibrium constants used to construct this speciation diagram are shown below:

Hydrolysis reactions

$UO_2^{2+} + nH_2O \Leftrightarrow UO_2(OH)_n^{(2-n)} + nH^+$
with n = 1 to 3 ; $\log \beta_n$ = - 5.2 (n = 1), - 11.9 (n = 2), - 19.2 (n = 3).
$pUO_2^{2+} + rH_2O \Leftrightarrow (UO_2)_p(OH)_r^{(2p-r)} + rH^+$
$\log \beta_{p,r}$ = - 5.62 (p = 2, r = 2), - 15.55 (p = 3, r = 5).

Complex formation by carbonate ions

$UO_2^{2+} + mCO_3^{2-} \Leftrightarrow UO_2(CO_3)_m^{(2-2m)}$
with m = 1 to 3 ; $\log \beta_m$ = 9.68 (m = 1), 16.94 (m = 2), 21.6 (m = 3).

Complex formation by organic matter A

(the charges are deliberately omitted)
$UO_2 + A \Leftrightarrow UO_2A$ $\log \beta = 5.4$
$UO_2(OH)_3 + A \Leftrightarrow UO_2(OH)_3A$ $\log \beta = 6.7$.

(1) Stœchiometry: study of the proportions in which, during a chemical reaction, the reagents combine and the products are formed. A reaction is said to be stœchiometric when the molar proportions of the reagents are identical to those in the chemical equation.

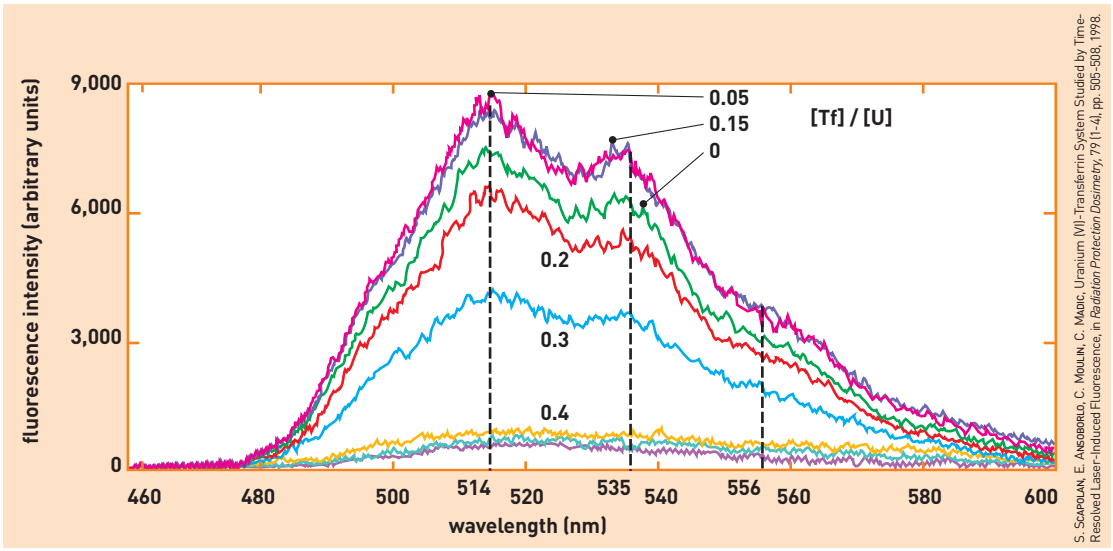
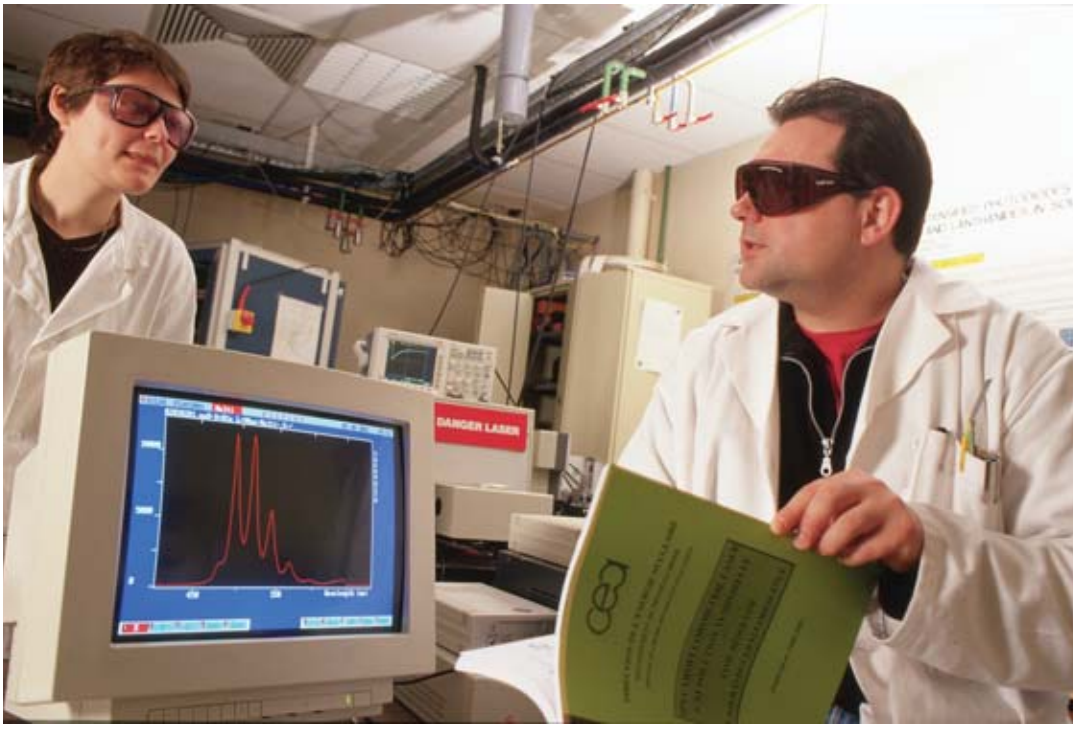


Figure 3.
Fluorescence spectra of uranium as a function of the ratio of uranium [U] and transferrin [Tf] concentrations. (Conditions of acquisition (identical for all the spectra): [U] 10^{-6} M, HEPES buffer and $NaCO_3$ 10^{-4} M, pH 7.4. Measuring gate delay 2 µs, duration 100 µs, integration time 20 s. Additions [Tf] 4.10^{-5} to reach the molar ratios 0, 0.05, 0.15, 0.2, 0.3 and 0.4).



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Analysis of a fluorescence spectrum obtained by Time-Resolved Laser Spectrofluorimetry (TRLS). Besides the speciation, this method allows to determine the first solvation sphere, the stœchiometry and the complexation constant.

ligand(s) studied. Also, using several methods affords the means to cross-check and validate results.
Obviously, the results derived from the use of these methods are meaningful only if the samples studied, whether synthetic or naturally-occurring, are handled and conserved under conditions that preserve their representativity (for example, maintenance of redox state by working in a glove box under a controlled atmosphere).

Towards the creation of an exchange scheme

Knowledge of speciation is an important point in many research areas, and in particular in those concerned by the Nuclear Toxicology Programme (human nuclear toxicology and **decorporation** procedures, study of biogeochemical cycles and depollution processes), for understanding and interpreting the mechanisms involved in the reactivity of elements present in trace amounts, and also for scaling associated experiments. This is assuming that the medium being studied is well characterised, that sensitive methods can be used to work at low levels of concentration and with radioactive materials (in particular for the study of actinides), that thermodynamic data bases are available, shared by chemists and biologists, and that methods of study and theoretical calculations are cross-checked.
The objective of the Cetama (see footnote p. 95) "Speciation" working group, which brings together CEA and non-CEA researchers, industrial partners, etc., is to set up an exchange scheme for researchers on these topics, in particular as regards data base and analytical speciation aspects.

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FOR FURTHER INFORMATION

OECD, *Evaluation of Speciation Technology*, Workshop Proceedings, 436 p., 2001 (ISBN 92-64-18667).

Douglas M. Templeton, Ariese Freek, Rita Cornelis, Lars-Göran Danielsson, Herbert Muntau, Herman P. Van Leeuwen and Ryszard Lobinski, Guidelines for terms related to chemical speciation and fractionation of elements. Definitions, structural aspects and methodological approaches (IUPAC Recommendations 2000), in *Pure Appl. Chem.*, Vol. **72**. No. 8, pp. 1,453-1,470, 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.

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.

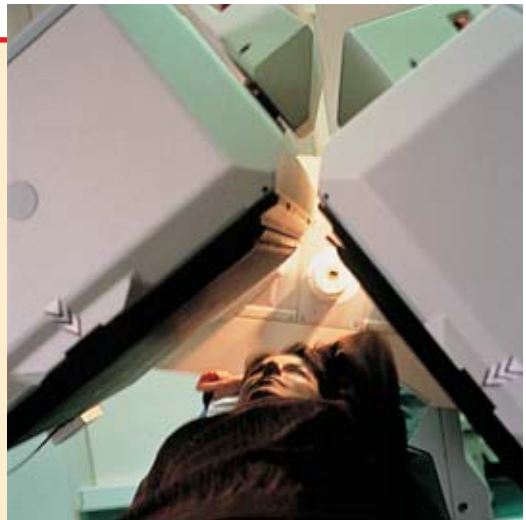
In the **Chernobyl accident** (Ukraine), which occurred in 1986, the total radioactivity dispersed into the atmosphere was of the order of 12 milliard milliard (10^{18}) becquerels over a period of 10 days. Three categories of radionuclides were disseminated. The first consisted of volatile fission products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



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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.

The CEA programme

The Nuclear Toxicology Programme was launched by CEA on October 1 2001 for a period of five years. It is a resolutely forward-looking programme comprising twelve projects that pool the expertise of physicians, biologists, chemists, physicists, etc. in the different Divisions of CEA. In 2003, this programme was opened up to France's other major public life science research bodies (Inserm, CNRS, Inra), and some projects are part of the European Commission's Sixth Framework Programme for Research and Technological Development (FPRTD).

The programme's central thrust is the *study of the biological effects of nuclear toxics*, i.e., all the compounds encountered in the nuclear industry that may have a chemical and (or) radiological toxicity towards living organisms. Its objectives are to study the toxicology of the materials used, in particular in nuclear **fuels**, to analyse the biological effects of **radionuclides** (naturally-occurring or artificial) that may be present in the environment, and to examine the effects of chemically toxic metals, particularly the **heavy metals**, used in nuclear research and industrial activities. For the radionuclides, the aim is to determine the potential health consequences of **exposure** to these materials and to make realistic estimates of the corresponding risks incurred.

The programme focuses on a range of **elements**: **carbon**, **cæsium**, **iodine**, **cobalt**, **strontium**, **selenium**, **technetium**, **tritium**, **americium**, **plutonium** and **uranium** for radiotoxicity, and **beryllium**, **boron**, **cadmium**, **lead** and again **cobalt** and **uranium** for chemical toxicity. One objective is to characterise their toxicity at the molecular and cellular level. Further elements will be examined as work proceeds.

The main research topics concern three types of mechanism:

- The mechanisms by which elements are transferred from the soil to plants, and transported from one cell to another.
- The mechanisms by which toxins accumulate in cell and tissue **compartments**.
- Specific detoxication mechanisms in bacteria, plants and animals.

In all cases, special emphasis is placed on work that makes it possible to compare the toxicity of different elements relative to a better known toxic chemical, such as cadmium or cobalt, and also, for as many elements as possible, work to compare chemical and radiological toxicity (cadmium, cobalt, etc.) when both stable and **radioactive** forms are present together. Special attention is paid to the toxicity of iodine[1], in particular to the mechanisms of its transport in the thyroid gland, and in other organs such as the mammary glands and the brain. To carry out this work, dedicated facilities are provided for the handling of elements of interest and the investigation of their effects on model organisms such as mice, plants and micro-organisms.

(1) Iodine, along with cæsium, was the most significant element released by the Chernobyl accident.