Measures to prevent the exposure of personnel to ionising radiation were taken as soon as the first nuclear laboratories were set up. This branch of occupational preventive medicine has since kept pace with advances in research and in the industrial applications of nuclear energy.

Specific features of occupational medicine in nuclear research and industrial applications

The first harmful effects of **ionising radiation** – "ray burns" (radiodermatitis) – were observed almost immediately after its physical properties were discovered. Years later between the two world wars delayed effects were demonstrated – leukemia among radiologists and researchers such as Marie Curie. Thus when the first CEA laboratories were set up in the late forties, measures to prevent exposure of personnel were implemented and research into **radioprotection** undertaken.

Francis Vigouroux/CEA

Radiographic examination at the occupational health service at the CEA Saclay Centre. A thorough system of medical monitoring was set up long ago in nuclear research and the nuclear industry.

At the same time, France voted in legislation to provide for preventive occupational medicine to monitor workers' health. Occupational medical services adapted to the specific hazards of **exposure** to ionising radiation were then set up. This medical monitoring has since kept pace with advances in research and in the industrial applications of ionising radiation, in particular the development of nuclear-fuelled electricity generation and the **fuel** cycle industry.

Several specific features

This branch of occupational medicine, which complements technical radiation safety provisions, is specific in several ways. The initial emphasis on possible hæmatological, skin or ocular effects resulted in the setting up of a thorough medical monitoring provision: six-monthly clinical examinations, blood tests, and specialist consultation (ophthalmology, for example).

Alongside exposure to ionising radiation in the strict sense, working conditions in hostile environments requiring personal protection equipment to be worn (e.g., breathing equipment for the protection of airways or special garments) require allowance to be made for the physical and psychological conditions associated with certain workplaces. Also, in both research laboratories and industrial plants, exposure to ionising radiation is often accompanied by exposure to chemical agents (see *Beryllium, an example of a non-radioactive nuclear toxic element*) and sometimes biological substances.

Specific investigation methods

The monitoring of internal exposure has required the development of specific investigation methods to measure, either ***in vivo*** or ***in vitro***, the **activity** incorporated by individuals.

In vivo measurement uses **whole-body gamma radiation measurement**, which determines the radiation emitted by the body, making allowance of course for the natural background level. This examination is used to detect radioactive iodine in the thyroid, and thoracic deposits of **fission products** or **actinides** in the lungs.

In vitro measurements, which are complementary, determine activity in excreta, namely urine or stools, after suitable preparation. In addition, measurement of activity on disposable nasal wipes is useful for the screening of exposure by **inhalation**.

The results of these examinations, carried out exclusively by specialised biological and medical analysis laboratories, reflect the processes of **metabolism** of the **radioelements**. To evaluate the **doses** for internal exposure, which will add to the doses measured by external exposure measurement devices, it is therefore necessary to make calculations with reference to models established by the scientific community.

MOX, not just uranium plus plutonium

Accurate knowledge of modes of exposure and of the physicochemical forms of radioelements is also most important. For example, uranium goes through different successive states during the fuel enrichment process: from solid to gas, oxide, fluoride, etc., which influence how it is transferred inside the body. Likewise, the behaviour of **MOX** fuel is not the simple sum of "uranium" and "plutonium" models, among other things because the mixture is never strictly homogeneous, and the particle sizes vary according to the manufacturing stage.

These aspects therefore require special complementary training of occupational health professionals and laboratory biologists, careful study of workplaces, reference radiobiology research – through CEA's Life Sciences Division for MOX – and analysis of the very highest quality.

Special care

In the event of a body **contamination** incident, medical personnel are required to dispense special care. For skin contamination, this includes cleaning procedures, mostly by washing with non-aggressive agents, to avert transcutaneous penetration.

In the case of internal contamination, special therapy is implemented, either to accelerate the natural elimination of the radioelement, or to trap it before it binds to target organs, using **chelating** agents such as, for example, DTPA for plutonium.

In the case of a contaminated wound, the occupation health physician may have to prescribe surgery with **dosimetric** monitoring.

Lastly, the medical monitoring of workers exposed to ionising radiation has long been governed by numerous regulatory prescriptions (Box G, ***The regulatory dose limits***, p. 72) that have often set standards for rules concerning other occupational hazards. For example they provide for individual medical files that group, among other data, the results of clinical and complementary examinations and a description of the exposure. This takes the form of work station or successive activity records based on workplace hazard assessment, and full dosimetric results. These files have to be kept for fifty years after the end of the exposure.

In the future, medical monitoring will have to adapt to new situations due to other occupational hazards arising from further scientific and technical advance, in particular from the operation of fourth-generation or thermonuclear fusion reactors.


Francis Vigouroux/CEA

Medical analysis laboratory at the CEA Saclay Centre. It is one of the laboratories equipped to carry out analyses specifically for occupational health and safety in the nuclear sector.


Cogema

Standard uranium fuel assembly for a pressurised water reactor. Handling its MOX equivalent requires special precautions.

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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-

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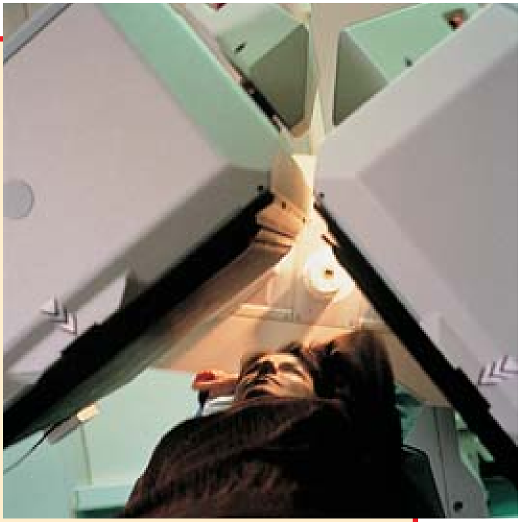
(1) m for metastable. A nuclide is said metastable when a transition delay exists between the excited state of the atom and the stable one.

A (next)



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.

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*).

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.

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(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.

G The regulatory dose limits

Gonin/CEA

Passing through a detector frame for individual contamination at the exit from a controlled area – here the Osiris reactor at CEA Saclay Centre – is a regulatory obligation.

Individual protection against the dangers of ionising radiation is based on two principles: (i) making sure a given radiation source irradiates exposed persons as little as possible (principle of optimisation), and (ii) making sure the exposure of a given individual remains below a certain level irrespective of the radiation source (principle of the dose limit).

These two principles are set out in the ICRP 60 recommendation published in November 1990(1) by the International Commission on Radiological Protection, the internationally recognised reference in the domain, and taken up in the Euratom 96/29 European directive of May 13 1996. The provisions of this directive were transposed into French law by the order of March 28 2001, the decree of March 8 2001 (modifying that of June 20 1966) and the decree of March 31 2003, which modify the public health and work codes accordingly.

Expressed in sieverts (Sv), the limits are of two sorts, global and local. Global limits are expressed in values of effective dose (Box F). It represents the acceptable risk level concerning the carcinogenic effect of ionising radiation. It is 20 mSv in 12 months for workers(2) in the nuclear field (in the broad sense) and 1 mSv per year for the general public. For a certain number of tissues and organs (skin, hands and feet, eye lens), a local limit is set with reference to deterministic risks of ionising radiation, namely radiodermatitis and cataract. This dose equivalent is thus set at 500 mSv for the skin and for the hands and feet, and 150 mSv for the eye lens. These values are ten times lower for the general public. These limits are for exposure resulting from human activities other than medical exposure(3).

The effective dose takes into account both external exposure and internal exposure.

For internal exposure, there are tables setting limits for each radionuclide, mode of exposure (inhalation-ingestion) and age, taking into account their ranging "transferability" in biological media, and the dose per unit intake (DPUI) coefficients expressed in sieverts per becquerel (Sv / Bq), the becquerel being the unit of activity.

They indicate the internal dose that is "committed" for 50 years in adults and up to age 70 for children, taking into account the effective half life of the radionuclide in question. Because of children's greater susceptibility to radiation and the possibility of longer exposure for radionuclides with long effective half lives, the most restrictive annual intake limits are for infants aged up to one year, and the least restrictive for adults from age 17 as prescribed in the ICRP 67 publication of 1993.

The "inhalation" and "ingestion" DPUI values take respectively into account the new values of digestive absorption and the latest lung model(4) of the ICRP.

From these regulatory limits, radioprotection experts can calculate "derived" limits of levels in air or on surfaces, for example, for internal exposure hazards.

Gonin/CEA

Dosicard dosimeter for real-time dosimetric monitoring.

(1) Superseding ICRP 26 published in 1977.

(2) Persons directly assigned to work with ionising radiation in industry, research and medicine.

(3) The treatment of hyperthyroidism by irradiation, for example, involves an organ delivered dose of 70,000 mSv!

(4) Publication ICRP 66 of 1994 on the modelling of the human respiratory tract for radiological protection, which supersedes the lung model of ICRP 30.