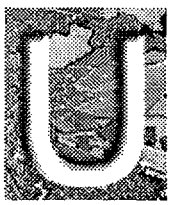
cea presse@aramis.cea.fr

# Uranium, uranium appauvri, effets biologiques

***Uranium, uranium appauvri, les utilisations de l'uranium et les caractéristiques des différents composés ; que devient l'uranium dans l'organisme, quels sont ses effets, dans quelles conditions l'uranium est-il un toxique chimique, un toxique radiologique***



Au CEA, physiciens, chimistes, biologistes développent des programmes scientifiques sur les propriétés et les utilisations des rayonnements ionisants. Depuis la création du CEA en 1945, de nombreuses recherches y ont été menées sur les propriétés de l'uranium naturel, enrichi ou appauvri, en collaboration avec des laboratoires universitaires et le CNRS. Les données sur l'uranium sont très nombreuses : depuis plus de 40 ans, des milliers d'analyses ont été publiées dans des revues internationales. Cette présentation sur l'uranium est une synthèse très succincte de toutes ces études.

## 1- Questions/réponses

- l'uranium 236 est-il plus toxique que l'uranium naturel ? pourquoi en parle-t-on ?
- quelle est la différence entre l'uranium soluble et l'uranium insoluble ?
- qu'en est-il au niveau des poumons ?
- quels sont les effets toxiques de l'uranium ?
- comment peut-on savoir qu'on a été exposé à de l'uranium ?
- l'uranium dans un aérosol est-il un toxique chimique ou radiologique pour le poumon ?
- l'uranium peut-il entraîner des leucémies ou des cancers ?

**Vous trouverez les réponses à ces questions dans ce document**

## 2- Dossier

1. `` l'uranium dans la nature " : qu'est-ce que l'uranium ? Où le trouve-t-on ?
2. `` caractéristiques de l'uranium " , chimiques et radioactives
3. `` différentes utilisations de l'uranium " : à partir de l'uranium de la nature, les différentes utilisations industrielles de l'uranium et leurs caractéristiques :l'uranium naturel, l'uranium enrichi, l'uranium appauvri
4. `` modes d'exposition à l'uranium " : ce que devient l'uranium dans l'organisme et combien de temps il y reste.
5. `` toxicité de l'uranium ", l'uranium est un métal lourd qui est aussi radioactif : quels sont ses effets toxiques ?
6. ``quelques valeurs de référence "

33/41 **Téléchargez ici le dossier complet**

## 1 – What is uranium? Where is it found?

Uranium is a metal (chemical symbol U) with atomic number Z = 92, in other words its nucleus contains 92 protons.

In the natural state it is formed of 3 isotopes associated with each other in the following proportions:

$^{238}U$ for which the nucleus contains 146 neutrons, accounting for 99.3% of the total
$^{235}U$ for which the nucleus contains 143 neutrons, accounting for 0.7% of the total
$^{234}U$ for which the nucleus contains 142 neutrons, in trace form (0.005%)

| isotope | Half-life (years) | % by mass | % by activity | Activity of each isotope (Bq/g) | Type of radiation emitted | Energy of alpha radiation |
|---|---|---|---|---|---|---|
| $^{238}U$ | 4.5 billion | 99.3 | 49 | 12 300 | alpha | 4.2 MeV |
| $^{235}U$ | 704 million | 0.7 | 2 | 80 000 | alpha, gamma | 4.5 MeV |
| $^{234}U$ | 246 000 | 0.005 | 49 | 227 000 000 | alpha | 4.8 MeV |

Half-life : time after which the radioactivity has reduced by half
Bq/g: Becquerel/gram. A Becquerel corresponds to one decayed atom per second
MeV: million electron volts.

*URANIUM IN NATURE*

**Levels in the environment**

Uranium exists in the natural state in all types of soil and rock, and particularly in granite. On average, its concentration in the earth's crust is 2 to 3 mg per kg, and about 3.3 µg per liter in sea water (1 µg is equal to one millionth of a gram). The content of some granites can be as high as 10 mg/kg. Uranium is also present in surface and subsurface water at a concentration of the order of one milligram per $m^3$. It also exists in natural water in very variable quantities; the highest contents in France are observed in the Massif Central, and are of the order of 50 µg/l (50 micrograms per liter).
The main ores from which uranium is extracted are uranite and pitchblende that contain between 0.1 and 0.5% of uranium. Exploitable ores are located in Australia, the United States, Canada, South Africa and Russia. French mines are no longer exploited.

**Levels in the human body**

Natural uranium regularly penetrates into the human body by ingestion or by inhalation. The daily ingestion from inhaled air is about 1 ng (1 ng is equal to 1 billionth of a gram). The average concentration of uranium in drinking water and in food varies depending on the geographic location. The average daily input through food and water is of the order of 2 µg; the quantity of uranium contained in the human body is about 90 µg.

## 2 – Uranium characteristics: chemical and radioactive

### Chemical characteristics of uranium

- Uranium is a heavy metal with a density close to 19 (similar to the density of tungsten, and 1.7 times the density of lead).
- Its melting point is 1130°C and its boiling point is 3850°C.
- It is a powerful reducing agent in the presence of water and is therefore easily oxidized in moist air and becomes yellowish.
- Uranium metal is pyrophoric: it ignites very easily when in aerosol form (like other elements, for example magnesium).
- It exists in many chemical forms in industry, in the solid, liquid and gaseous states:
  - Hexavalent compounds ($UF_6$, $UO_2F_2$, $UO_2(NO_3)_2$ and ammonium duiranate $U_2O_7(NH_4)_2$) are the most stable and are the most biologically soluble forms,
  - Tetravalent compounds ($UF_4$, $UCl_4$) other than oxides (mainly $UO_3$) are medium soluble.
  - Oxides ($UO_2$, $U_3O_8$) and hydrides ($UH_3$) are only very slightly soluble.

### Radioactive characteristics of uranium

Although uranium in the natural state is formed of three isotopes, all of which are radioactive, there are many other artificial isotopes varying from $^{218}U$ to $^{241}U$, all of which are also radioactive. The most abundant is the $^{238}U$ isotope (see concentration of natural uranium, above).

The three main isotopes 238, 235 and 234 decay mainly by emitting high energy alpha radiation (from 4 to 5 MeV) but with a very short pathway, only a few millimeters in air and a few micrometers in water and in biological tissues. The accompanying beta and gamma radiation is low energy, except for gamma radiation from uranium 235.

Each isotope passes through successive decay states to produce descendants that form a very long decay chain. The decay chain for $^{238}U$ passes through 13 intermediate nuclei. For example, the descendants of uranium 238 are the isotopes $^{234}U$, radium 226 (half-life 1600 years) and radon 222 (half-life 3.82 days), to produce lead 206, which is a stable element, after a few billion years. The descendants include protactinium 234 that is a very short half-life beta emitter, but with high energy (1.1 and 2.3 MeV). This beta emission is used for the detection of natural uranium.

The radiological characteristics of natural uranium are due mainly to the characteristics of the 238 isotope.

All descendants are present in natural uranium in uranium ore, in other words in uranium in nature, and are in equilibrium. This means that for each descendant of uranium at each moment, the number of radionuclides produced by the radionuclide preceding it in the chain is the same as the number of radionuclides that disappear to produce the radionuclide following it in the chain. Since the different radionuclides in the chain have very different half-lives, an extremely long time (several millennia) is necessary to reach this equilibrium.

Only the above three isotopes $^{238}U$, $^{235}U$ and $^{234}U$ are present in natural uranium metal that has been through an industrial process. The descendants are eliminated and will gradually reappear and equilibrium will be restored as a function of their half-lives; six months for thorium 234 and protactinium 234, to several thousand years for radium 226. Due to the very long half-lives of the three isotopes of natural uranium, the alpha activity per unit mass is low (about 25 000 Bq/g at the time of manufacturing compared with 50 000 Bq/g for natural uranium in equilibrium with its descendants).

In depleted uranium obtained during the natural uranium enrichment process (see chapter 3), the descendants were eliminated along with some of the $^{235}U$ and the $^{234}U$. The initial activity per unit mass is of the order of 16 000 to 22 000 Bq/g as a function of the degree of depletion; the total activity per unit mass (alpha and beta) after reaching an equilibrium with the initial descendants is of the order of 40 000 Bq/g.

In depleted uranium produced in reprocessing (see chapter 3), there are weak traces of other isotopes such as uranium 232 (half-life 70 years and activity = $8 \times 10^{11}$ Bq/g) and uranium 236 (half-life 23 million years and activity $2.4 \times 10^{6}$ Bq/g).

| | | | U natural | | U depleted (type 1) | | U depleted (type 2) | | U (type 3) | |
|---|---|---|---|---|---|---|---|---|---|---|
| Isotope | Half life years | Activity (Bq/g) | Content (%) | Activity (Bq/g) | Content (%) | Activity (Bq/g) | Content (%) | Activity (Bq/g) | Content (%) | Activity (Bq/g) |
| $^{232}U$ | 70 | $8.5 \times 10^{11}$ | - | - | - | - | $<10^{-7}$ | $8.15 \times 10^{2}$ | $2 \times 10^{-9}$ | 16 |
| $^{233}U$ | 159 000 | $3.57 \times 10^{8}$ | - | - | - | - | - | - | - | - |
| $^{234}U$ | 246 000 | $2.3 \times 10^{8}$ | 0.0056 | $1.29 \times 10^{4}$ | 0.003 | $6.9 \times 10^{3}$ | 0.003 | $6.9 \times 10^{3}$ | 0.01 | $2.3 \times 10^{4}$ |
| $^{235}U$ | 704 million | $8 \times 10^{4}$ | 0.718 | 5.74 $10^{2}$ | 0.25 | $2 \times 10^{2}$ | 0.3 | $2.4 \times 10^{2}$ | 0.63 | 5 $10^{2}$ |
| $^{236}U$ | 23.4 million | $2.39 \times 10^{6}$ | - | - | - | - | 0.1 | $2.39 \times 10^{3}$ | 0.01 | $2.39 \times 10^{2}$ |
| $^{238}U$ | 4.5 billion | $1.23 \times 10^{4}$ | 99.27 | $1.23 \times 10^{4}$ | 99.74 | $1.24 \times 10^{4}$ | 99.6 | $1.24 \times 10^{4}$ | 99.35 | $1.23 \times 10^{2}$ |
| Total activity (Bq/g) | | | | 25 800 | | 19 400 | | 22 700 | | 36 100 |

- Type 1 depleted uranium: after enrichment of natural uranium
- Type 2 depleted uranium: after enrichment of uranium originating from reprocessing a fuel for a PWR reactor
- Type 3 uranium: after reprocessing of uranium originating from a natural uranium reactor.

*Note:*

- Values given for the content and activity for the 3 typical examples of depleted uranium are approximate values.

The specific activities of natural and depleted uranium only include the activities of uranium isotopes; they are representative of the radioactivity of natural or depleted uranium that has just been formed.

**3 – The various industrial uses of uranium starting from natural uranium, and their characteristics (natural uranium, enriched uranium, depleted uranium).**

There are essentially two types of uses of uranium:

- As a heavy metal (for example in the same way as lead or tungsten); the most frequent uses include materials for ship keels, aircraft wings and control surfaces, shielding against biological effects of radiation and weapons such as ammunitions for armed forces.

- As a fuel in nuclear power stations, as an energy source due to the fundamental property of the $^{235}U$ isotope of being 'fissile" (it is the only natural element with this property); when bombarded by neutrons, a fissile reaction takes place creating firstly two new nuclei (fission products) and neutrons, and also producing energy. The created neutrons are used to trigger a chain reaction so that the energy is produced continuously. This is the operating principle of a nuclear reactor used in nuclear power stations to generate electricity.
  Therefore, $^{235}U$ is the nuclear "fuel".

**The different types of depleted uranium**

The following diagram summarizes the methods used to obtain depleted uranium.

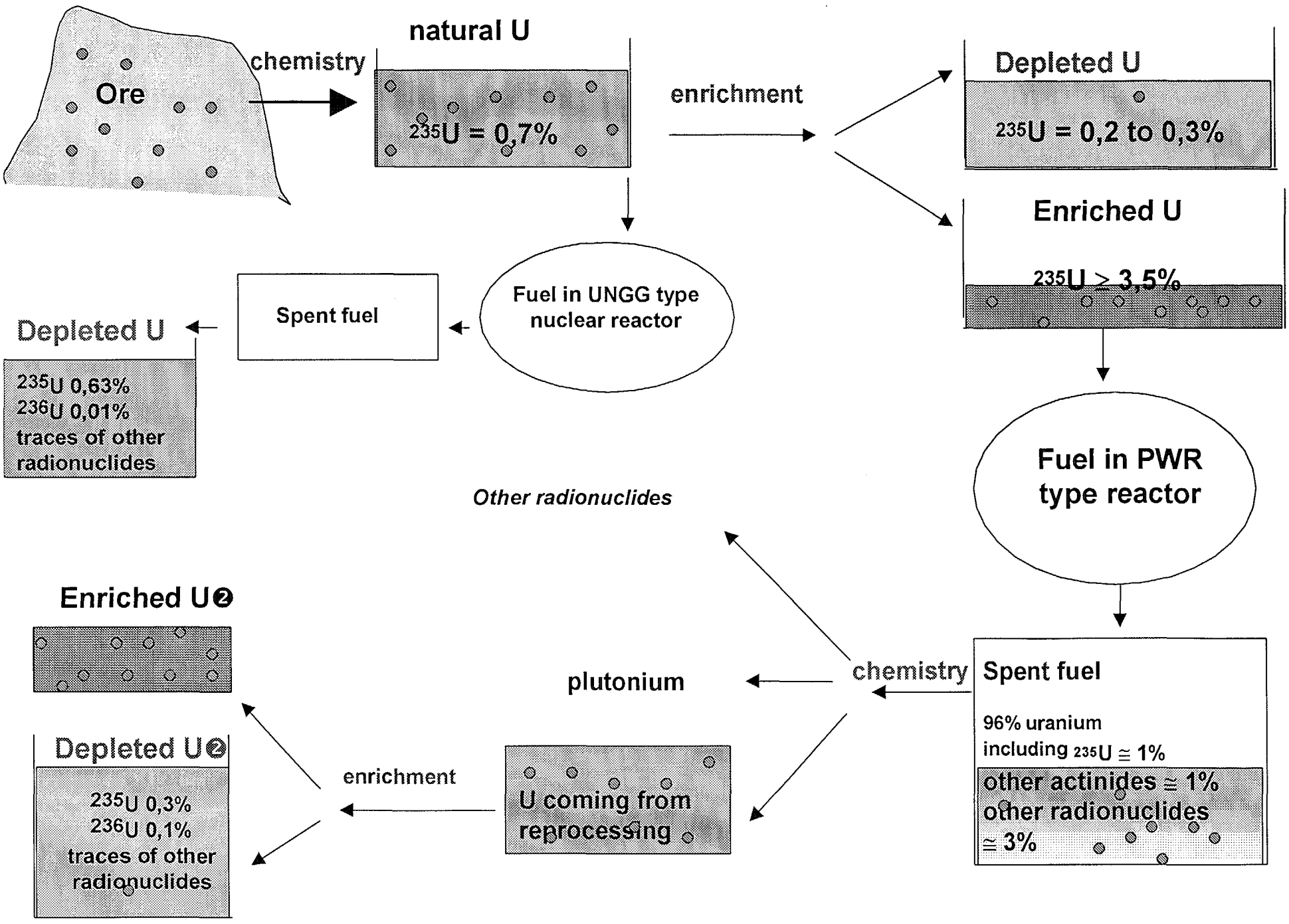
**<u>Type 1 depleted uranium</u>**

The proportion of $^{235}U$ necessary to create chain reactions in nuclear power stations operating with a conventional water reactor (PWR, pressurized water reactor) is greater than the proportion found in natural uranium, and is of the order of 3.5%. The engineering operations by which this content is increased are called "enrichment" operations. "Enriched" uranium is obtained from natural uranium (this is the objective), but "depleted" uranium (therefore with a lower content of $^{235}U$ than natural uranium) is also obtained at the same time.

The proportions of uranium isotopes in this depleted uranium are (typical values):

99.75% for $^{238}U$
0.25% for $^{235}U$
0.003% for $^{234}U$.

It is different in that the proportion by mass of $^{235}U$ is lower than that found in natural uranium. It usually contains 0.2 to 0.5% of uranium 235, compared with 0.72% for natural uranium.
There is no difference in the chemical toxicity of the two forms of uranium.


Ore
chemistry
natural U
$^{235}U$ = 0,7%
enrichment
Depleted U
$^{235}U$ = 0,2 to 0,3%
Enriched U
$^{235}U \geq 3,5\%$
Fuel in UNGG type nuclear reactor
Spent fuel
Depleted U
$^{235}U$ 0,63%
$^{236}U$ 0,01%
traces of other radionuclides
Fuel in PWR type reactor
Other radionuclides
Enriched U2
Depleted U2
$^{235}U$ 0,3%
$^{236}U$ 0,1%
traces of other radionuclides
enrichment
U coming from reprocessing
plutonium
chemistry
Spent fuel
96% uranium
including $^{235}U \cong 1\%$
other actinides ≅ 1%
other radionuclides
≅ 3%

The diagram shows a second method of obtaining depleted uranium (type 2 depleted uranium and type 3 uranium) obtained from fuel previously used in a nuclear reactor.

**Type 2 depleted uranium**

In a reactor that uses enriched uranium as fuel (PWR type), the depleted uranium is obtained by applying enrichment operations after reprocessing of the used fuel output from the reactor. This fuel (that contained 96.5% of $^{238}U$ and 3.5% of $^{235}U$ when it entered the reactor) is composed of about 95% of $^{238}U$, 1% of $^{235}U$ and 1% of elements in the actinides family (other uranium isotopes and particularly $^{236}U$, plutonium, etc.) and 3% of fission products created as a result of nuclear reactions in the reactor. Uranium isotopes separated during reprocessing operations applied to this used fuel can then be subjected to a new enrichment operation itself generating depleted uranium. Typical values of the proportions of isotopes present in this depleted uranium are then 99.6% of $^{238}U$, 0.3% of $^{235}U$, and of the order of 0.1% of $^{236}U$, plus traces of $^{232}U$, $^{234}U$, plutonium and fission products.

**Type 3 uranium**

One type of reactor uses natural uranium directly as its fuel (the UNGG (uranium natural graphite gas) reactor in which the reactor fuel is natural uranium, the moderator is graphite and gas is used as a heat transporting fluid). At the exit of the reactor, this fuel (used fuel) contains uranium isotopes, plutonium, and other elements in the family of actinides and fission products as a result of the nuclear reactions that took place in the reactor. Reprocessing operations consist of separating the uranium from the plutonium and other radionuclides. When applied to this used fuel, the result is uranium with the typical composition of 99.35% of $^{238}U$, 0.63% of $^{235}U$, 0.01% of $^{234}U$, 0.01% of $^{236}U$. There are also traces of $^{232}U$, plutonium and other radionuclides, in other words in quantities so low that they cannot be measured.

The average activities of these different types of depleted uranium are summarized in the table in chapter 2. The concentration of uranium 235 (0.63%) in type 3 uranium actually makes it more like natural uranium (content 0.72%) than other types of depleted uranium.

## 4 –Ways of exposure to uranium, what happens to uranium in the body and how long it remains

The quantity of natural uranium in the human body may be increased in variable quantities resulting from various human activities. There are three main pathways including inhalation, ingestion and passage through the skin due to deposition on the skin or an injury.

### 4-1 Inhalation

- Inhalation is followed by deposition of particles in the bronchial tubes and the deep part of the lungs (the alveoli). In the same way as for all dust in the air, the distribution of particles in a uranium aerosol to the different levels of the respiratory system depends on the diameter of the particles, and only the smallest can reach the deepest part of the lung; for example 29% of particles with a diameter of 0.1 micrometer reach the alveoli, whereas only 5% of particles with a diameter of 5 micrometers can reach the alveoli (reference average diameter for radiation shielding). Large particles (diameter of more than 10 micrometers ) are blocked in the upper part of the respiratory system and are transported to the digestive tube and then eliminated in faeces.

The diameter of inhaled particles is a very important parameter that needs to be known to estimate the proportions of uranium that resides in the lung for a long period, and uranium that is eliminated quickly through the digestive tract.

Two different types of phenomena may be observed, depending on the pulmonary deposit and the solubility of uranium compounds:

- Soluble inhaled uranium compounds may enter the blood stream and then be distributed throughout the body, be deposited in bone and in the kidney and be eliminated, essentially in urine.
- Particles of insoluble compounds migrate slowly from the lung to the lymphatic system.

### 4-2 Ingestion

Uranium can be ingested through water and food. Many physiological and chemical factors, including the solubility of the compound, have an influence on the absorption of uranium in the digestive tube. The International Commission on Radiological Protection (ICRP) gives a transfer rate from the digestive tube to blood equal to 2% for a soluble compound and 0.2% for a slightly soluble compound.

### 4-3 Skin contamination

There is no particular danger related to irradiation due to deposition of natural or depleted uranium compounds on the skin (weak penetration of emitted radiation, low global radioactivity, etc.), and in the case of soluble forms, a very low proportion (0.04%) can pass through the skin to enter the body; however, the incorporated quantity may be very high in the case of an injury, usually in the form of particles or splinters a few millimeters long. If these fragments cannot be surgically removed, the uranium in them dissolves very slowly.

**4-4 Behavior of uranium in the body**

The future of uranium in the body depends on three main mechanisms : blood transfer, deposition and retention in organs, and excretion.

Regardless of the way of exposure, most uranium in the blood is in soluble form.

- Therefore uranium is very quickly transferred from the blood to the different organs and is excreted in urine.
- The main two organs that retain uranium are bone and the kidneys. In bone, uranium behaves much like calcium, but most uranium that becomes fixed to the bone surface is released again into the blood. A small quantity that becomes fixed in bones can remain there for several years.
- Most plasmatic uranium is quickly excreted in urine; 60 to 70% of uranium in the blood is eliminated in urine within 24 hours, and about another 10% is eliminated in the next 5 days.

The quantity of uranium in urine in different persons varies from 0.3 to 1 µg/liter, depending on our environment and dietary habits. Accidental intakes can easily be identified by an urine analysis.

## 5 – Toxicity of uranium - uranium is a heavy metal and is also radioactive; what are its toxic effects?

### 5.1 Chemical toxicity

**The chemical toxicity is due to the chemical reactivity of uranium that, like all chemical elements, depends on the peripheral characteristics of the atom; it is independent of the isotope (characteristic of the nucleus of the atom)**

Natural uranium has an essentially chemical toxicity, particularly for the kidney; the first signs of toxicity of uranium, particularly for soluble forms, are looked for in the kidney. But all compounds interact with the kidneys, as demonstrated by the limiting values given in the next section. A severe exposure (of the order of one milligram in the kidneys) causes lesions of the tubular cells and deterioration of the kidney function that can cause nephritis or kidney insufficiency. Kidney damage can be detected early by the analysis of some proteins or enzyme activities in urine.

The American Nuclear Society fixed the kidney toxicity threshold at 3 µg per gram of kidney several decades ago. This estimate is currently being debated, and represents a limiting value of about 1 mg for the kidneys since the average weight of two kidneys is 300 g.
This limiting value corresponds to exposure by inhalation to 30 mg for very soluble uranium compounds, and 250 mg or more for medium soluble or slightly soluble compounds.

Furthermore, uranium in insoluble form may be toxic in the lung where symptoms similar to those caused by metallic and/or inert dust aerosols can be observed; lesions in the lung are the result of a large accumulation of uranium and dust particles from the environment.

Note that uranium 238 and its decay products are incorporated through the food chain (food and drinking water) naturally every day, and that the average daily intake is of the order of 2 micrograms.

### 5.2 Radiological toxicity

In the case of isotopes contained in natural uranium, the very slow radioactive decay (half-life varying from several million to several billion years) is the reason why most toxic effects are due to the chemical properties of the uranium, the magnitude of these effects depending on the incorporated quantity. The radiological toxicity is governed by the toxicity of uranium 238 but even this is very low; uranium 238 is a very low activity alpha emitter, which means that one microgram of 238 uranium emits about one alpha particle per minute.

The 232 and 233 isotopes of uranium can have radioactive toxicity, since their half-lives are shorter than the half-lives of the other isotopes and therefore their radioactivity is higher *(see the " characteristics of uranium" chapter)*. These isotopes cause cancer of the bone in mice, after the injection of about 400 000 Bq of one of the two isotopes. The excess number of tumors is greater with uranium 232 that has a much shorter half-life (70 years) than that of uranium 233 (159 000 years). Under the same experimental conditions, the injection of natural uranium does not cause the appearance of tumors, but it is only possible to inject about 25 Bq of natural uranium (1 mg/kg), since higher injected quantities quickly become toxic for the kidney (*see "chemical toxicity"*). However, there are very few studies on the

specific effects of uranium 232 and 233 since it is difficult to obtain them "pure" and therefore the risk of cancer is calculated as a function of the incorporated quantity.

The radiological effects of depleted uranium are similar to the effects of natural uranium *(for further details see the "characteristics of uranium" chapter)*, regardless of whether it is obtained directly from natural uranium or from reprocessing uranium. In the latter case, depleted uranium contains a very low proportion of other radionuclides, namely less than 1 ten millionth of each which in no way modifies the global radioactivity.

The irradiation doses to the body after exposure to depleted uranium are directly proportional to the radioactivity and the radiological effects (cancers, leukemia) depend on the received dose:

- the radioactivity of depleted uranium is of the same order of magnitude as the radioactivity of natural uranium, regardless of its origin,
- despite the many studies, no effects have ever been found in the case of natural uranium;

The point of view of international organizations

- The EPA (the USA Environmental Protection Agency) has not classified natural uranium as a carcinogen
- The IARC (Internationnal Agency for Research on Cancer, an organization forming part of the World Health Organization – WHO) does not classify natural uranium by inhalation as being a carcinogen to man due to lack of data establishing a cause to effect relation (inadequate evidence of carcinogenicity).

Thus, natural uranium becomes chemically toxic at quantities very much smaller than quantities that could cause radiological toxicity. Since a large proportion of uranium is eliminated in urine, an increased incorporation of uranium is followed by increased excretion in urine. **Measurement of uranium in urine** is the essential link in the method used to monitor exposure at work or by accident.

• **Under known usage conditions in research work and in industry,**

the chemical hazards due to natural uranium are similar to hazards due to other heavy metals, particularly in the kidneys.

The human body appears to tolerate the ingestion of natural uranium through the food chain very well.

No research work and no studies carried out on persons exposed to natural uranium have ever demonstrated that bone, kidney or lung cancer can be caused by incorporation of natural uranium into the body. There is a great amount of data on this subject, including data for persons working on uranium that are strictly monitored throughout all operations in the uranium cycle (from extraction of the ore that generates dust, until the production of fuel for nuclear power stations).

**There is no radiological risk until the incorporated quantities of uranium are high enough so that chemically toxic effects on the kidneys would be real**.

Studies on depleted uranium in the forms used in the nuclear industry do not show any difference in biological behavior for exposure to depleted uranium and to natural uranium. Consequently, chemical toxicity is dominating.

• **In recent wars, in the Gulf War and in Bosnia and Kosovo,**

depleted uranium weapons were used to perforate armor ( ou " were used as armor-piercing "??). The impact of weapons on their targets is accompanied by vaporization of metallic depleted uranium. Particles of this aerosol ignite and are oxidized when they come into contact with air.
Consequently, the conditions of exposure at the time of this type of firing may be different from the conditions encountered in an industrial environment, either in terms of the physicochemical form due to the particular oxidation conditions of vaporizing and igniting metal particles, or the particle size.

There is no reason why the radiological risk related to the impact of depleted uranium weapons should be any different from the risk caused by natural uranium, since the radioactivity levels of the two forms of uranium are similar. But the non-radiological risk could be modified to the extent that the physicochemical properties and the particle size can influence the biological behavior of this aerosol, and the biological effects may be different from the biological effects of industrial aerosols. This is why it should be useful to carry out studies on these particular exposure conditions.

## 6 – Some reference values

The following values are suggested by different international scientific organizations, and some of them are used directly in European and French regulations.

The proposed values and limits are guides to determine an appropriate protection under exposure conditions at work and in the environment. They are not danger limits; caution is necessary when using them to estimate the risk of occurrence of a biological effect or a disease; real conditions of exposure must be taken into account.

### Uranium in the air

- French regulations state that, considering the chemical toxicity of soluble uranium compounds, quantities inhaled in a single day must not exceed 2.5 mg of uranium regardless of the isotopic composition of the uranium.

- data in the legislation or recommendations for working environments in the United States are given in a table. These values given by the NIOSH (National Institute of Occupational Safety and Health), the OSHA (Occupational Safety and Health Administration), and the ACGIH (American Conference of Governmental and Industrial Hygienists) are determined for an exposure of 8 hours per day.

| Organization | ACGIH | NIOSH | OSHA |
|---|---|---|---|
| Soluble U compounds | | 0.05 $mg/m^3$ | 0.05 $mg/m^3$ |
| Insoluble U compounds | 0.2 $mg/m^3$ | 0.25 $mg/m^3$ | 0.2 $mg/m^3$ |

Given that the inhalation rate for a standard man at his workstation is 1.2 $m^3$ per hour corresponding to approximately 10 $m^3$ for an 8-hour work shift, it can be seen that the values in the table give limiting values for inhaled quantities equal to 2 to 2.5 mg per day for insoluble compounds of uranium and 0.5 mg per day for soluble compounds.

### Uranium carried in water and food

- French regulations state that quantities ingested in a single day must not exceed 150 mg of uranium, regardless of its isotopic composition, due to the chemical toxicity of soluble compounds of uranium

- The EPA (Environmental Protection Agency) suggests a value of 3 µg/kg/d as a reference dose (RfD) as the quantity of soluble uranium salts that can be ingested without an appreciable risk of an effect harmful to health.

- The World Health Organization (WHO) fixes guide values for chemical elements to guarantee lack of toxicity in drinking water consumed daily (based on 2 liters per day for an adult). The WHO has suggested a provisional guide value equal to 2 µg uranium / liter of water.

It may be difficult to respect this value in regions in which the uranium quantity is naturally high due to technical problems with the removal of uranium from water, since concentrations before treatment can be as high as several tens or hundreds of µg of uranium / l.

**European regulations on the effects of radioactivity**

European directive 96/29, May 13 1996, (basic standards for protection of the health of the public and workers against dangers resulting from ionizing radiation) sets the limiting annual irradiation value equal to 1 mSv for members of the public and 100 mSv over 5 years for workers. The dose is calculated from factors called "Doses per Incorporation Unit (DPUI)" expressed in Sv/Bq. These DPUI values are calculated for each isotope and for different exposure conditions, particularly as a function of the exposure pathway (inhalation, ingestion), the solubility of the compound (there are 3 classes, soluble "F", slightly soluble 'M" and insoluble "S") and the age at the time of exposure (from nursing infant to adult). These values are derived from recommendations made by the International Commission on Radiological Protection (ICRP).
For example, to evaluate exposure of the public:

DPUI values after ingestion (water and food) by the adult are:

for $^{238}U$, the DPUI is $4.5 \times 10^{-8}$ Sv/Bq
for $^{235}U$, the DPUI is $4.7 \times 10^{-8}$ Sv/Bq
for $^{234}U$, the DPUI is $4.9 \times 10^{-8}$ Sv/Bq
The solubility of compounds is taken into account by using the digestive transfer factor (called the f1 factor) that is equal to 2% for soluble compounds and 0.2% for slightly soluble compounds.

DPUI values after inhalation of a uranium 238 aerosol by an adult with average particle sizes equal to 1 micrometer are as follows:
- for a soluble compound: the DPUI is $5 \times 10^{-7}$ Sv/Bq
- for a medium soluble compound: the DPUI is $2.9 \times 10^{-6}$ Sv/Bq
- for a very slightly soluble compound: the DPUI is $8 \times 10^{-6}$ Sv/Bq

All DPUI values are given in the appendices part of the text in European Directive 96/29.

For drinking water, European directive 98/83, November 3 1998 (quality of water for human consumption) fixes a guide parametric value for radioactivity equal to 0.1 mSv per year, which is 10% of the annual dose limit for members of the public.
Based on normal consumption (2 liters per day for an adult), the limiting concentrations based on radiological toxicity criteria are estimated at:
- 245 µg/l for $^{238}U$
- 114 µg/l for natural uranium

After making these calculations, it is found that the limiting concentration given by the WHO for uranium as a chemical element based on data about toxicity to the kidney, is significantly more severe than the limiting concentration calculated based on radiological toxicity data. For natural uranium, there is a factor of about 50 between the value given by the WHO and the value derived from European Directives.