URANIUM

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Introduction

Uranium was discovered in 1789 by M. H. Klaproth while analysing the mineral petchblenda (believed to be an oxide mix of iron, zinc and tungsten) to which he gave the name Uranium to celebrate the discovery of the new planet in the solar system, discovered in those years. In 1789 Zirconium was discovered as well, an element of fundamental importance for nuclear reactor technology.

The element and its properties

Uranium, in standard conditions, is a hard radioactive metal, silver-white in colour, malleable and ductile. It is quite common in nature but it is difficult to find it in high concentrations and on average it is present in the terrestrial crust in a proportion of about 3 grams of uranium per ton of crust (also called part per million, ppm): since the terrestrial crust is estimated to be $3X10^{19}$ tons, about 10^{13} tons of uranium are available (10000 billion tons), a greater quantity than silver, gold or molybdenum.
Uranium is constituted by various isotopes (atoms of the same chemical element, with the same atomic number but different mass number) present in different percentages in the terrestrial crust:

- ^{238}U 99.2745%
- ^{235}U 0.72%
- ^{234}U 0.0055%

In nature about 200 minerals exist containing uranium, rarely found in isolation and more commonly present in various types of rocks, among which in particular granites (acid rocks) and siliceous rocks; smaller concentrations are present in basaltic and sedimentary rocks.
Uses of uranium. Uranium, before nuclear energy was discovered, was used primarily to stain glass. Today uranium is used primarily as a fuel in nuclear plants where the fissile material is constituted by isotope ^{235}U.
An endless reservoir? After having individuated an uranium presence in the terrestrial crust, it is necessary to evaluate a reservoir, that is individuate how many tons of uranium it contains. The reservoir has to be considered exploitable, otherwise we could say that the crust is an “enormous reservoir” since it contains 3 grams/ton of uranium, but we do not have a technology that allows its low cost extraction. An uranium reservoir is defined as exploitable once an economic limit has been defined, that is a threshold that allows a classification: reservoir evaluation is a problem of international norm.

Uranium resources

When you talk of “retrievable” uranium, it means that it is possible to extract the mineral from a reservoir and make it available for a fuel element, at a specific price that is expressed in dollars. Analysing the world map of reservoirs and knowing their nature it is possible to assess the exploitable quantity of uranium by forming cost ranges: up to 40 $, between 40 $ and 80 $ and between 80 $ and 130 $. Obviously the most economical are the ones that are exploited first. All areas where there is an attested presence of uranium are denominated **Reasonably Assured Resources** (RAR).

One the reasonably safe reservoirs are known, through analyses coupled with adeguate radioactive measures, similar areas in geomorphologic terms can be individuated in order to obtain information on reservoirs similar to the ones being exploited. These reservoirs are considered esteemed and are part of the **Estimated Additional Resources** (EAR, also known as Inferred Resources, IR). These extra resources are classified in two categories: EAR-I and EAR-II; the EAR II are less certain than the first ones. There is also another category called Speculative Resources (SR), which derive from another extrapolation of the geomorphologic characteristics of land that could easily obtain uranium.

The RAR resource types are the easier ones to exploit, thus cheaper; they are available in quantities that go between 507,400 t and 4,587,200 t in relation to how much money is available for the extraction. The data relating to the Estimated Additional Resources of the second group (EAR-II) are much more precise in comparison with those on Speculative Resources and the estimates are of a quantity of uranium equal to about 2,200,000 tons at a price between 80 $ and 130 $. The Speculative Resources also include uranium in phosphates and it can be estimated in about 22,000,000 tons of uranium. If we add the uranium container in the oceans' water, we reach a quantity of uranium equal to about 4 billion tons!

The technology of uranium extraction from phosphates is essentially developed: it is already used in Belgium and the United States. However, it has a limited diffusion because it is not economically convenient: it is estimated that an extraction project of 100 tU/year would have a cost in the range 60-100 $/kgU (inclusive of investment costs). For what concerns the extraction of uranium from the sea, encouraging research has been undertaken in Japan: however, it is still a technology tested at laboratory level with very high costs, estimated around 300 $/kgU.

The cycle of nuclear fuel

Nuclear fuel is subject to a cycle throughout its life. Obvious preliminaries are all the mining operations, which are followed by a long and complex series of various purification processes, with the primary aim of eliminating the elements that absorb neutrons. Neutrons are particles capable of starting the fission process by breaking the U-235 nucleus with subsequent release of energy: if there are elements that absorb neutrons, these cannot produce fission reactions ("neutron poisons"). The operations undertaken in this first part of the fuel cycle are mainly of a chemical nature and lead to the production of a gaseous compound of uranium (uranium hexafluoride, UF_6) that allows the enrichment process of the isotopeU-235. This phase is necessary since the majority of nuclear reactors uses fuel made of enriched uranium: on average the enrichment is around 3% of U-235, against 0.72% of U-235 in the uranium found in nature. If we send the gaseous compound of uranium hexafluoride to a centrifuge it is possible to discriminate the different mass of the isotope U-235 compared to the isotope U-238 and it is possible to concentrate an isotope compared to another. Gaseous ultracentrifuges constitute the enrichment plants: other enrichment processes are possible through the gaseous diffusion plants or the laser selective isotopic separation. The enriched hexafluoride is successively converted in uranium dioxide (UO_2) powder, which is assembled in pellets that, appropriately canned, will constitute the fuel element. Nuclear fuel is thus inserted in nuclear reactors and produces energy until the end of its life. At this stage the fuel element has become radioactive and it is put into pools, usually near the reactor, in order to reduce the radioactivity level.

Exhausted fuel can have two different endings: the definitive deposit in areas with appropriate geological characteristics or reprocessing. During its time inside the reactor not all U-235 is burned (about 1% is left) and in the meantime, because of nuclear reactions, other nuclides have been born that can produce a nuclear fission reaction: fissile nuclei such as plutonium, PU-239, born from U-238 through the "fertilisation" process. These can be used in turn as nuclear fuel, while the remaining fuel must be stocked in definitive deposits.

The reprocessing alternative, which is used by some countries like France and the UK, has some advantages: first of all it allows a more rational exploitation of fuel, allowing not only the recovery of the left over U-235 but also the newborn PU-239 that represents an extremely important resource because it descends through fertilisation from U-238 and represents the great majority of the uranium found in nature. Secondly, the reprocessing allows to substantially reduce the volume of highly radioactive products that require long term stocking. Finally reusing already irradiated reduces considerably the risk of proliferation by making material treated twice unsuitable for the production of nuclear weapons.

A look at the future

The current fuel cycle exploits, with current reactors, just a small part of the energy that can be extracted from uranium found in mines and leaves a legacy of waste that has to be confined for long periods of time. It is obvious that, to truly close the cycle and to fully exploit the potential of the nuclear fuel available in nature, it is necessary to have not only thermal reactors with high burning rates but also "fast" type reactors, where neutrons do not undergo a slowing process to kick-start the fission reaction. These reactors are capable of exploiting much better the fuel found in nature with a totally different production of waste, a lot less problematic compared to current reactors. At the current rhythm of nuclear energy production uranium resources translate into a 65-year energy availability with current reactor consumption equal to 66.000 tons/year. However, the exploitation of Estimated Additional Resources of the second group (EAR-II) would guarantee energy for another 260 years without any retreatment process. Considering also the Speculative Resources and neglecting the uranium contained in the oceans there would be another 360 years of energy production available. Currently the supply of uranium is based for 50-60% of the total on extraction from mines, while the rest derives from:

- stock of natural uranium and/or enriched uranium of civil or military origin. In the previous years more uranium than necessary has been extracted: this has caused a build-up of the element, partly due to a limited development of nuclear energy;

- production compared to what was expected;
- reprocessing of exhausted fuel;
- use of 235U of military origin, which derives from the dismantling of nuclear warheads.

Radioactivity and man

Radioactivity is the phenomenon in which some unstable nuclei transform into others with the emission of particles. Radioactivity is as old as the Universe and is present everywhere: in the stars, in the Earth and in our own bodies. In fact, man has been exposed to radiation since when he appeared on Earth. Radioactivity was discovered at the end of the 19th Century thanks to the work of Henry Becquerel and Pierre and Marie Curie who in 1903 received the Nobel Prize in Physics for their important contribution to scientific knowledge. They discovered that certain minerals possessed the property of spontaneously emitting radiation: these minerals, such as uranium, radium and polonium, for example, were called “active” and the phenomenon regarding the emission of radiation was called “radioactivity”.

Atoms and matter

All matter that surrounds us is made up of atoms. Every atom consists of protons and neutrons, which together form the nucleus, surrounded by a cloud of negatively-charged electrons. Within the atom, the nucleus is made up of positively charged protons and by neutrons that lack electric charge and are therefore neutral (as their name indicates). Atoms are electrically neutral because the number of protons is equal to the number of electrons. The total number of protons in the nucleus (and therefore of electrons in the outer cloud) determines the identity of a chemical element: for example, the chemical element with 8 protons is oxygen, the one with 26 protons is iron, the one with 79 protons is gold and the one with 92 protons is uranium.

Isotopes. A chemical element can have, besides the fixed number of protons that characterise it, a varying number of neutrons: in this case there will be different isotopes of the same element. For example, iron present in nature has four isotopes with 26 protons but with 28, 30, 31 and 32 neutrons respectively. Isotopes of the same element can be distinguished by their mass numbers (neutrons + protons): hence you can find iron-54, iron-56 etc.

There are about 90 elements that occur in nature (ranging from the lightest, hydrogen, to the heaviest, uranium) and nearly 270 isotopes. Among these elements, about twenty have only one stable isotope (for example, sodium, cobalt, arsenic and gold) while others have at least two stable isotopes (for example, chlorine has two, zinc has five and lead has ten). In addition to the isotopes present in nature (natural isotopes) nowadays there are a great number of artificial, man-made isotopes, such as cobalt-60 (27 protons, 33 neutrons), used in radiotherapy or plutonium-239 (94 protons, 145 neutrons) used as a nuclear fuel.

A question of stability. Almost all natural isotopes are stable contrary to artificial isotopes that are unstable, i.e. they tend to arrange themselves spontaneously in new nuclear structures that are energetically more favourable. The transformation of an isotope into another is called disintegration or decay, and unstable isotopes are known as radioactive isotopes (radioisotopes or radionuclides). This process of spontaneous disintegration of atomic nuclei, during which ionising radiation is emitted, is called radioactivity. Ionising radiation is any particulate or electromagnetic radiation capable of modifying the structure of matter with which it interacts. In the case of biological tissues, this interaction can damage the cells. In the majority of cases the damage is repaired by the normal defence mechanisms in the organism but at times the affected cells could be impaired with negative consequences on the health of the individuals exposed. The extent of the damage also depends on the magnitude and length of exposure.

The time taken for an isotope to decay can be short or very long. The half-life of a radioactive isotope is defined as the time it takes for half of the atoms of a pure sample of the isotope to undergo decay into another element. The half-life is a measure of the stability of an isotope: the shorter the half life, the less stable the atom is. For example, the half-life of uranium-238 (92 protons and 146 neutrons), one of the isotopes that has been present in the Earth's crust since its formation, is 4.47 billion years. At present, the amount of uranium-238 left after decay is about half the original quantity present on Earth, which has been estimated to be about 4.5 billion years old.

How is radioactivity measured?

Radioactivity is measured in disintegrations per second and its unit of measure is the Becquerel (Bq), in honour of the physicist Henry Becquerel who discovered the spontaneous emission of radiation from uranium in 1896. As mentioned above, the radiation produced by the disintegration of radioisotopes interacts with matter, transferring energy. The magnitude and the gravity of the effects depend on the dose and the type of radiation received. For example, small doses of ultraviolet radiation from the Sun are harmless to man, but an excessive exposure can cause sun burns. The unit of measure of the absorbed dose is the gray (1 Gy = 1 joule absorbed by 1 kg of matter). To give a measure of the biological effects caused by radiation the concept of equivalent dose has been introduced. This allows the evaluation of the damage caused by the same dose of different types of ionising radiation. In this case, the unit of measure is the sievert (Sv). For a chest X-ray, 0.14 mSv are administered (mSv = millisievert, i.e. one thousandth of a Sv), for a mammography, 1mSv.

Exposure to radiation

Since his appearance on Earth, man has been exposed to natural radiation to which he has adapted perfectly. The dose of natural radiation to which each living organism is exposed every year is about 2.4 mSv. This natural radiation comes from two sources: the Earth, deriving from radionuclides present in the Earth's crust such as potassium-40, uranium, thorium and radon (the gas that is the largest component of natural radiation) and outer space, in the form of cosmic rays.
In addition to natural radiation, there is man-made radiation, which can be produced in different ways. The most important is radiation for medical diagnostic purposes and radiotherapy. Radioactive elements can also be released into the atmosphere as a result of atomic experiments and nuclear power plant accidents (e.g. Chernobyl).

Man can be exposed to radiation in two ways:

- external exposure (or irradiation) that occurs when the radiation source is outside the organism;
- internal exposure, or internal contamination, that occurs when an individual ingests or inhales radioisotopes.

Ionising radiation can have immediate or long-term effects on man. The former can be observed a short time after exposure to radiation and depending on the magnitude of the dose can be mild, such as nausea and vomiting, or more serious, such as damage to the hematopoietic tissue. Long-term effects include cancer and leukaemia.

Radioprotection

Once the harmful health effects of exposure to ionising radiation were ascertained, it became essential to formulate adequate protection measures. As a consequence, radioprotection was born, a set of measures aimed at guaranteeing protection of workers, the population and the environment against the risks of ionising radiation.
The basic rules of radioprotection are the following:

- move away from the source of radiation, since the intensity of radiation decreases with increasing distance from the source (for example: nuclear power plants are surrounded by a “respect zone” which prevents the establishment of human activities in the immediate neighbourhood);
- interpose shielding material between the source and humans (for example: in nuclear plants, the protection of workers and the surrounding environment is ensured by radiation shields made of thick walls of lead, steel, concrete or other special materials)
- reduce the length of time of exposure to radiation to a minimum.

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