

Nuclear

Introduction

Nuclear power is the source of energy that has been able to conquer, in only fifty years, a share that is over 6% of the sources of primary energy and to cover over 15% of world consumption of electricity (*Source: BP Statistical Review of World Energy - June 2010*).

However we consider the distribution of energy, of final energy consumption in Europe, to be around 23% electricity and 77 % fuels, and consequently even though all the electric energy were to be produced by the nuclear plants, this would cover only a quarter of our energy consumption.

Production of nuclear power is a long, complex, polluting and energetically costly process. The principal uranium mines in the world are in remote areas and extraction of the mineral requires a lot of work: in order to obtain 160 tonnes of uranium, required to operate a standard power plant for one year, starting with the granite rock that is rich in uranium, in a proportion of 1000 parts per million, 160000 tonnes of material are required, and an even larger amount of rock must be moved. In fact, after having identified the presence of uranium in the Earth's crust, an assessment of the deposit needs to be made, in other words it is necessary to identify how many tonnes of uranium it contains and it is considered exploitable depending on economic limits. Since twenty years, the number of nuclear power plants in the world has been fundamentally stable and in 2010 the number was 441 units (*Source: www.iaea.org*).

Nuclear knowledge

What is it

The atom is the matter unit and for a long time it was considered indivisible. Actually, it includes a nucleus (containing protons and neutrons) surrounded by a cloud of electrons distributed over layers corresponding to the different energy levels and from which they can migrate or into which they can crowd causing chemical reactions and the creation of chemical compounds (or substances or products). Each time the atom nuclei undergo a transformation and join to create a larger nucleus (fusion) or split into two or more smaller nuclei (fission) energy is produced.

The use of nuclear energy as an energy source is widely debated, especially with reference to the risk of uncontrollable accidents. Nuclear energy can be produced by means of both the nuclear fission (progressive splitting of the nuclei of heavy radioactive elements) and fusion (joining the nuclei of light elements). Of the two reactions, fission is the only one viable for human beings, but it does not exclude the possibility of accidents and the production of radioactive waste. As regards to fusion, it is still impossible. No device has yet been created to contain and maintain hydrogen "confined" for a sufficient time at a very high temperature allowing the aggregation of nuclei.

What it is for

The heat generated during the transformation of nuclear energy into thermal energy, regardless of it being obtained from uranium or plutonium, can be used to obtain mechanic energy, i.e. to move a machine (e.g. a turbine). The efficiency of this transformation depends on the temperature at which the boiler can operate, i.e. the nuclear reactor. The mechanic energy is then converted into electricity by an alternator connected to a turbine.

Nuclear fuels are used, for example, to produce energy on big ships and submarines. The energy provided by nuclear motors is useful both to move propellers and for the other services on board.

In the past researchers studied the possibility to transform the nuclear energy directly into chemical energy or to use the heat directly for heating purposes or to allow the production of the metal industry. Today such hypotheses have been discarded since they are not economically viable and also for safety reasons. Following that decision, the operating temperature of many nuclear power plants was reduced, thus limiting dangers but also efficiency. After those modifications, a nuclear reactor today supplies heat at a lower temperature as compared to a traditional thermoelectric

power plant.

Nuclear energy can also be used to cure some human diseases, especially tumours. Patients suffering from certain types of tumour can be subject to a radiation therapy by using very complex equipment. The radiations, produced by the machines and adequately oriented, kill the tumour cells.

Where it is

As is the case with other non-renewable energy resources, such as coal, oil and natural gas, the question is how much nuclear fuel is available on the Earth and at what price.

There is a huge quantity of natural uranium. The oceans, for example, contain approximately one billion cubic kilometres of uranium. Technically, the extraction of the "sea-uranium" is feasible but it would cost 30 times more than the current market prices.

In 2009, the total quantity of the extractable uranium on the mainland at economically sustainable costs exceeds 3,7 million tonnes (Source: International Atomic Energy Agency (IAEA) – Red Book, Uranium: Resources, Production and Demand, June 2010). In particular, a higher concentration of it can be found in rocks containing uranium. The total quantity of available uranium is apparently very large, but it is markedly downsized when it is compared to the necessary quantity to operate a reactor.

To produce nuclear energy on a large scale a sufficient quantity of natural uranium at a reasonable cost is needed. In particular, the enrichment process and the dedicated equipment need to have a sufficient capacity and the enrichment prices need to be reasonable.

Moreover there is a need to assess the economic viability and the effectiveness of the reprocessing equipment to treat the nuclear fuel already used in the reactors to recover the still "un-burnt" uranium.

In short, the costs of the nuclear power plants are to be assessed with a view to the whole nuclear energy cycle, which is much more complex than that of other energy resources. Costs include: the whole fuel cycle, building and operating the plant, including emergency cases, disposing of the waste and dismantling the plant.

Nuclear fission

Fission is the breaking of the nucleus into two fragments through the action of neutrons on very heavy nuclei, i.e. uranium 235. The main effects of this phenomenon are: the release of a large quantity of energy and the simultaneous emission of 2-3 neutrons that activate a reaction, provoking new fissions and starting a chain reaction. During nucleus fission energy is released and, if kept carefully under control, it can be exploited to produce electricity. Some of these heavy elements, like uranium 235 (92 protons and 143 neutrons), are located in deposits and in order to obtain them it is necessary to extract them from the soil. Others, like plutonium 239 or uranium 233, are artificially produced by men.

Nuclear fusion

Nuclear fusion is the process that since ancient times has used solar and star energy to activate fusion reactions between hydrogen nuclei.

Fusion reaction starts from very light nuclei that aggregate. By joining together, they become heavier and loaded with a great "binding energy". For example, a mixture of hydrogen nuclei (1 proton), deuterium and tritium (1 proton and 1 or 2 neutrons) can trigger a reaction which, through various passages, leads to the creation of carbon nuclei.

In order to let the reaction occur, the two reacting particles must have a sufficient quantity of kinetic energy to overcome the repulsive barrier created by the electric charge of the nuclei. This means that it will be necessary to reach extremely high temperatures, where the matter is in plasma state. The most studied reaction, which is also the least difficult, is "deuterium plus tritium", with a trigger temperature of 100 million degrees centigrade. Deuterium is an isotope (atom of an element with the same number of protons, but with a different number of neutrons) of hydrogen, whose nucleus is made up of a proton and a neutron. It is present in water with the proportion of 1 out of 7,000 atoms of normal hydrogen, therefore it cannot be depleted. Tritium is another hydrogen isotope, made up of a proton and two neutrons. It is

radioactive, with a half-life of 12 years and it is produced by bombing lithium by means of neutrons. Indirectly, lithium is therefore the energy raw material.

Radioactivity

Radioactivity is indeed a physical phenomenon in which unstable nuclei are transformed into nuclei of other elements or isotopes (identical atom nuclei from the chemical viewpoint but with different mass, owing to the different number of neutrons) of the starting nuclei, by emitting nuclear radiation. The core, before decaying to a lower energy level, can remain in a radioactive state for a period of time ranging from a fraction of a second to 100 million years.

Radioactivity is also a natural phenomenon but, in the majority of cases, at lower levels. Moreover, it should be remembered that, if kept below certain levels, radiations can even be useful, help certain diagnostic and healing treatments such as X rays, nuclear medicine and “rays” against certain cancer cells. However, each exposition is to be controlled in terms of both duration and intensity and should also comply with all the relevant safety norms, as regards both patients and doctors and specialist technicians. However, above a certain limit, radiation can become very dangerous for human health also with reference to the exposition time.

Radioactivity is dangerous especially in those elements marked by a “half-life” (transformation into other nuclei) which may last thousand of years and can stabilise inside the bodies of human beings or other living organisms.

A bit of history

The instability of nuclei and the freeing of ionising radiation (each electromagnetic radiation capable of producing ionisation in atoms or molecules of the body it goes through, i.e. the ejection of an electron from the atomic structure with the ensuing creation of a pair of ions, positive and negative) is present naturally but it started being considered from the scientific viewpoint only on the occasion of the study of the x rays conducted by Roentgen in 1895. During the 20th century vital research was conducted leading to the atomic fission.

First of all, in 1934 Mr. and Mrs. Curie identified the first case of artificial radioactivity. In 1942, after a series of “home-made” experiments in the legendary Roman institute in Panisperna street, the Italian physic Enrico Fermi carried out the first fission experiment under controlled conditions. Thus, the first nuclear reactor was created at the University of Chicago. That research belonged to the effort made by the American scientists which three years after led them to manufacture and drop the first atomic bomb on the Japanese city of Hiroshima (80,000 killed instantly).

After the world war, in 1954, the first electro-nuclear power plant – albeit moderately powerful (5 megawatt) – started operating in the Soviet Union. The first nuclear power plant aimed at the production of electric energy to be sold on the market dates back to 1956 and was built near Calder Hill, in England.

During the second half of the last century the production of electric energy from nuclear fuel increased up to 17% of the world energy production. In particular, at the end of 1996, the world counted 439 operating nuclear power plants and 43 being built. The United States has the largest nuclear capacity in the world (29%), followed by France (18%) and Japan (12%). In terms of percentage contribution of nuclear energy to the production of household electric energy, Lithuania is in the lead (83%) followed by France (77%9, Belgium (55%) and Sweden (46%).

In the last years the development of nuclear energy was negatively influenced by several factors: the reduction of investments in this field; the Chernobyl nuclear accident (1986); the poor development of waste disposal techniques; the growing difficulties faced by some countries in operating and maintaining the older power plants and finally the latest accident which took place in 1999 in Japan.

Following a referendum, in July 1990 Italy completely abandoned the use of nuclear energy to produce electric energy and the two nuclear power plants existing at the time were decommissioned.

Uranium

The element and its properties

Uranium was discovered in 1789 by M. H. Klaproth while analysing the mineral pitchblenda (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.

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 3×10^{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 adequate 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)**. 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 and EAR-I resource types are the easier ones to exploit, thus cheaper; they are available in quantities that go between 3.500.000 t and 4.500.000 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 16.000.000 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 contained 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 graph shows the geographic position of uranium resources (RAR and EAR-I) for a total quantity of 3.537.000 tons.

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 ^{235}U 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 isotope ^{235}U . This phase is necessary since the majority of nuclear reactors uses fuel made of enriched uranium: on average the enrichment is around 3% of ^{235}U , against 0.72% of ^{235}U 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 ^{235}U compared to the isotope ^{238}U 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 ^{235}U is burned (about 1% is left) and in the meantime, because of nuclear reactions, other nuclids have been born that can produce a nuclear fission reaction: fissile nuclei such as plutonium, ^{239}Pu , born from ^{238}U 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 ^{235}U but also the newborn ^{239}Pu that represents an extremely important resource because it descends through fertilisation from ^{238}U 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 ^{235}U of military origin, which derives from the dismantling of nuclear warheads.

Some calculations for the future

The consumption of nuclear fuel depends on the type of reactor where it is used (thermal reactor or fast reactors), on the type of treatment given to exhausted fuel (with or without reprocessing) and on the expenses we are willing to bear for uranium extraction (keeping in mind that the cost of fuel weighs on the cost of the energy produced for about 20%).

Taking as a reference the nuclear energy produced in 2002 (2570 TWh) we can make some predictions regarding the duration of uranium resources on the basis of the technology used for combustion and of the type of exploitable resources.

Obviously these estimates have to be corrected with the effective values of electricity produced with nuclear power, which are increasing compared to 2002.

It is foreseen that from now to 2020 demand for uranium will increase, from a minimum of 10% (up to 73.496 tU/year) to a maximum of 29% (up to 86.190 tU/year) compared to today, on the basis of projections respectively by shortcoming and excess of the installed electronuclear power.

All data are taken from sources NEA and IAEA 2002.

Nuclear plants

Electronuclear plants

A nuclear power plant allows the production of steam without using fossil fuels. A nuclear reactor behaves like any boiler and the steam it generates can be used to operate a turbine connected to an electricity generator.

In particular, the “heart” of the reactor of a fission nuclear power plant is called “core” and generally has the shape of a cylinder. The core is made of a liquid, for example water, into which cylindrical uranium bars are dipped, a couple of metres long and with a diameter of a few centimetres.

At regular intervals there are control bars capable of absorbing many neutrons. Thus, the chain reaction is kept under control and stopped, if necessary. In the most common type of reactors, the water contained in the core is warmed by the

fission of uranium and is circulated by means of a pump until it reaches a heat exchanger, into which it cools down producing steam which, in its turn, rotates the turbine of the plant.

A reactor is classified according to the type of fuel, the type of coolant and the core's inner architecture. For example, a common distinction is made between light water and heavy water reactors.

Light water reactors

In light water reactors the fuel is made of cylinders of uranium oxide enriched with uranium 235. The water circulates among the cylinders and acts both as a controlling element and as coolant.

The core is hosted in a pressurised steel container provided with the coolant intake and outlet holes. Shields to absorb the nuclear radiation are mounted around the container and the active parts of the reactor: the metal heat shield mainly absorbs gamma radiation, the concrete biological shield absorbs neutrons. Of course the safety and emergency systems necessary to face possible nuclear accidents are paramount.

Heavy water reactors

The fuel of heavy water reactors is made of non-enriched natural uranium. There are more modern reactors called "fast" reactors, cooled by means of liquid metal and working with highly enriched fuel by converting uranium 235 into plutonium. The French Superphenix produces 1200 electric megawatt with a 40% total efficiency. However, such plants show several limitations, including the cost of the energy produced, 2-3 times higher that of a light water power plant.

Fusion reactor

The fusion reactor works according to the opposite principle to the fission reactor. The fission reactor divides the nuclei of heavy atoms and the resulting heat is released in order to heat water and activate, through the water vapour, a turbine that produces electricity. Instead in the fusion reactor, light atoms (hydrogen isotopes deuterium and tritium) are united into a helium atom (fusion). The fusion frees a bit more energy than the fission and does not produce any radioactivity.

In the fusion, only if two nuclei are located very close one to the other, the force of nuclear attraction melts them. The problem is that this force only act at very short distances, at thousand billion parts of a millimetre, and as the nuclei that are going to be melted are both positively charged, when they get closer, they tend to push back and do not melt due to another force, i.e. electrostatic repulsion, that acts on bigger distances and hamper the fusion.

In order to break that barrier, the nuclei have to be in excitement state, at more than a hundred million degrees temperature, when atoms are detached from their electron "shell". This is the condition when the fusion naturally occurs between light atoms.

The extremely high temperature that is needed to fusion plasma (the ionised hot mixture of deuterium and tritium, hydrogen isotopes), i.e. several million degrees, has not allowed to build a fusion reactor at industrial level. Nevertheless, the research is continuing to make important progress and the objective seems to be approaching.