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Principles of Nuclear Power

This Factfile summarises the main principles underlying nuclear power.

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Summary

This Factfile summarises the main principles underlying nuclear power: the structure of atoms, the concept of fission, chain reaction and the essential elements of a power reactor.

Elements and Atoms

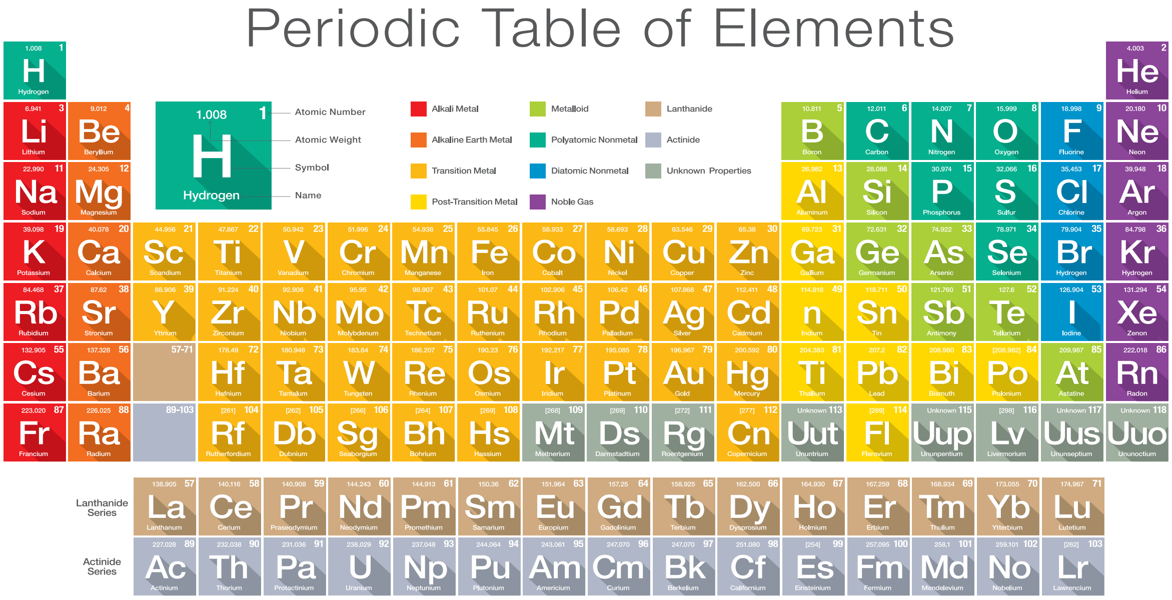
All materials in the universe are made up of elements in different chemical combinations. As far as the earth is concerned, ninety-two elements occur naturally. The smallest particle of an element is called an atom, although atoms themselves consist of three sub-atomic particles, protons, neutrons, and electrons. Protons and neutrons are found in the core, or nucleus, of an atom, and are surrounded by a “cloud” of electrons ‘moving in orbits’. The nucleus contains virtually all the mass of the atom.

The identity of an atom is established by the number of protons in its nucleus. This number must always equal the number of electrons in the cloud. Thus, the simplest element, hydrogen (H), has one proton and one electron, whilst the most complex naturally occurring element, uranium (U), has 92 protons and 92 electrons.

All elements, however, are capable of having different numbers of neutrons in their nuclei. Although a hydrogen atom does not usually have any neutrons, there are two further forms of hydrogen atoms with either one or two neutrons in their nuclei.

These are called deuterium and tritium, respectively. These versions of the element hydrogen have different physical properties and are called isotopes of hydrogen. They are unusual in having specific names. Uranium, for example, occurs naturally as a mixture of two isotopes, known simply as U^{235} and U^{238} in the approximate proportion of 0.7% to 99.3%. This means that it consists of uranium atoms, each having 92 protons and electrons, but with either 143 or 146 neutrons.

In any chemical reaction, such as when carbon is burnt in oxygen to form carbon dioxide (as happens in a coal burning power station), the nuclei of both types of atom are unaltered - all the reactions take place in the electron cloud. Therefore all the original atoms are still there but rearranged into new compounds. In nuclear power stations, this is no longer the case because nuclear reactions also involve the nucleus and produce materials with different numbers of protons and neutrons from the original material.

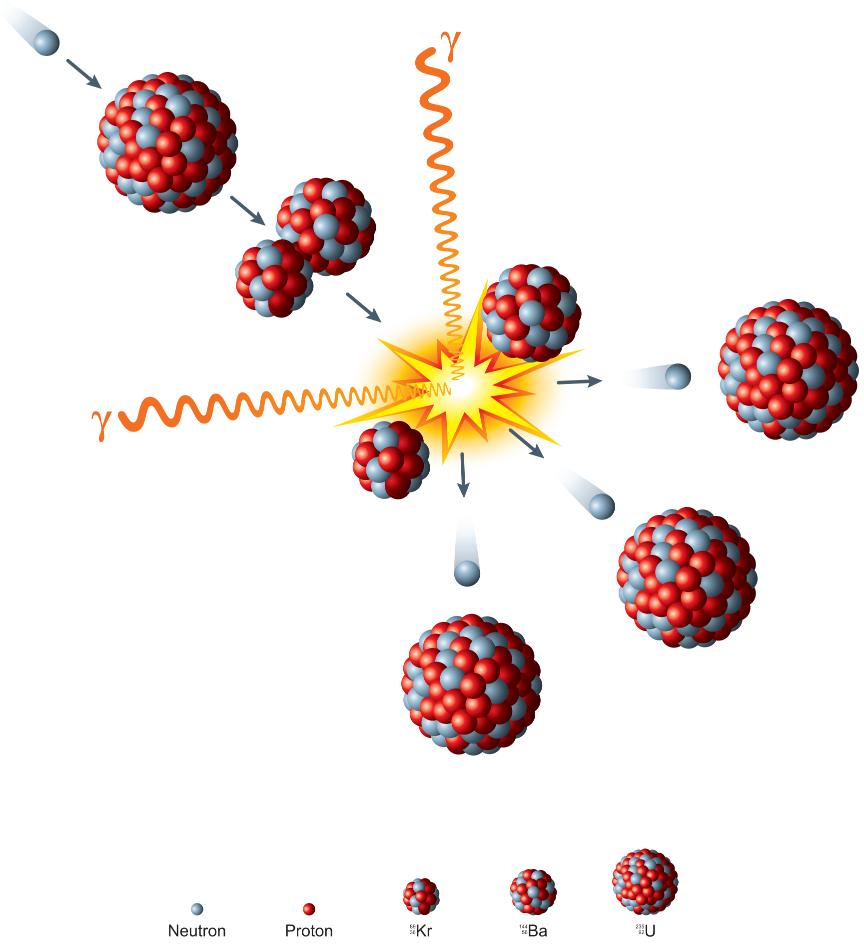


Fission and the Chain Reaction

The isotopes of most naturally occurring elements are very stable, which means that they do not change with time. If, however, the nucleus of an isotope such as U^{235} absorbs an extra neutron, then it may split in a process known as nuclear fission. When this happens, each atom of U^{235} splits into two or more atoms which, of course, correspond to other elements since each will have a number of protons, neutrons and electrons. Typical products of such a fission process are the elements, strontium, iodine and xenon, but there are many other possibilities. In any case, the fission products which form initially can disintegrate further so that the eventual mixture of elements within a sample becomes more complex.

In addition to the production of new elements, the fission of each U^{235} atom produces, on average, 2 or 3 free neutrons, each of which has the potential to trigger the fission of another U^{235} atom. Substances such as U^{235}, capable of such fission reactions, are known as fissile materials. If enough neutrons released by the fission process go on to trigger further fissions, a chain reaction is set up which is self-sustaining, and which can be put to use as a source of a considerable amount of energy in the form of heat.

The importance of U^{235} is that it is a naturally occurring fissile material with a controllable chain reaction, and is the obvious fuel for a nuclear power station. In most types of nuclear reactor, however, the amount of U^{235} in the fuel has to be increased above that occurring in natural Uranium in order to make the nuclear chain reaction self-sustaining. This is achieved by a process of Uranium enrichment.



Schematic showing nuclear fission

Radiation

During the splitting of an atom of U^{235}, or any other fissile nucleus, radiation is produced. Any material producing radiation is called radioactive. There are four distinct types of radiation associated with nuclear fission, called α (alpha), β (beta), γ (gamma), and neutron radiation:

- Alpha radiation is basically the atomic nucleus of the element helium (He) consisting of two protons and two neutrons. Alpha-radiation is not very penetrative; for example, it is unlikely to pierce human skin. The danger to man arises if an alpha-emitting element, such as plutonium, is lodged in the body. The alpha-radiation can then be very damaging.
- Beta-radiation consists of electrons or their positively charged counterparts, positrons. It can penetrate the skin, but not very far.
- Gamma-radiation is penetrative in a manner similar to x-rays and has similar physical properties. It can be stopped only by thick shields of lead or concrete, for example. Like x-rays, it is a form of electromagnetic radiation, as is visible light.
- The fourth type of radiation consists of the neutrons emitted during the fission process. Neutrons are also very penetrative, but less so than gamma-radiation, and have an effect on human tissue approximately midway between beta and gamma-radiation.

In general terms, the heavier and more energetic the radiation, the greater the damage to human tissue.

High level waste: image courtesy of Selafield

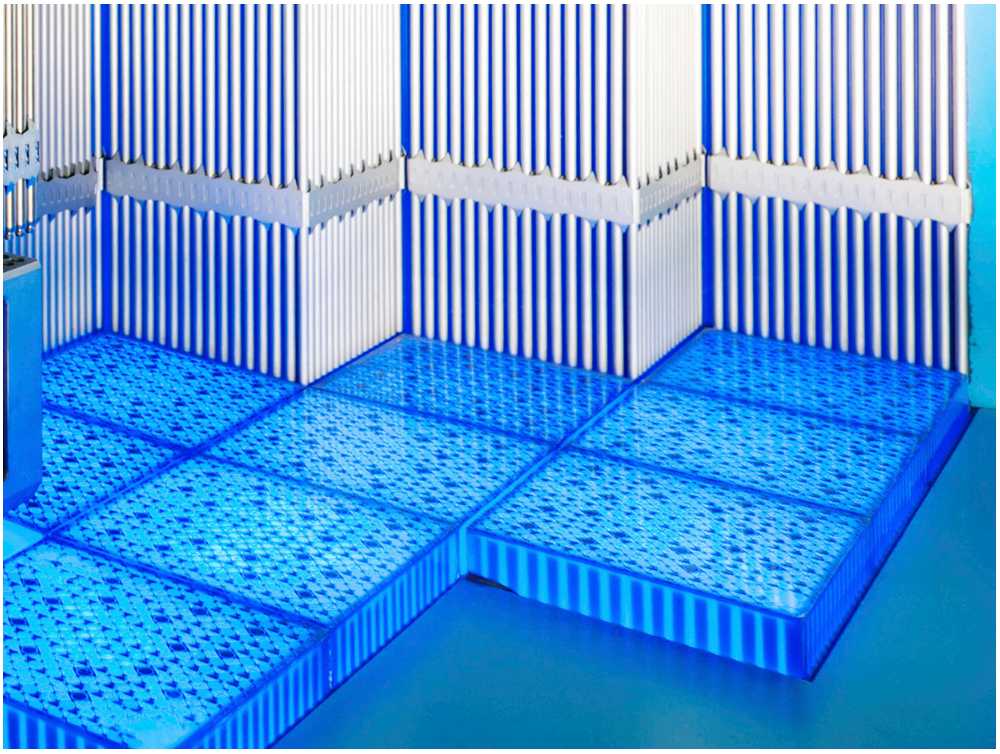
Fast Neutrons and Moderators

In the early 1940s physicists postulated that if the fast moving neutrons produced by the fission process could be slowed down to velocities that are sometimes called thermal velocities, then the U^{235} atoms would capture them more easily. They proposed that this could be done by using a moderator material to slow down the neutrons without absorbing them.

Two of the most useful moderators are carbon, which is used in the form of very pure graphite, and deuterium, a naturally occurring isotope of hydrogen. Deuterium is used in the form of deuterium oxide, or "heavy" water, small quantities of which can be found in natural water (itself usable as a moderator). A nuclear reactor which uses a moderator to slow neutrons to thermal velocities is called a thermal reactor.

The first thermal reactor was assembled by Fermi and his associates at the University of Chicago. It was a cubic lattice of lumps of natural uranium dispersed in a pile of graphite blocks (hence the term atomic pile). The lumps were about 10cm in diameter spaced about 30cm apart. By building the pile slowly, Fermi was able to monitor neutron activity and predict when the pile would go critical, that is when the chain reaction would become self-sustaining. This happened on 2 December 1942, and the heat power developed was 1/2 watt, later increased to 200 watts.

This first reactor was of enormous significance. It showed that a chain reaction could be induced and controlled, and it was the prototype for the controlled power reactors that have followed.

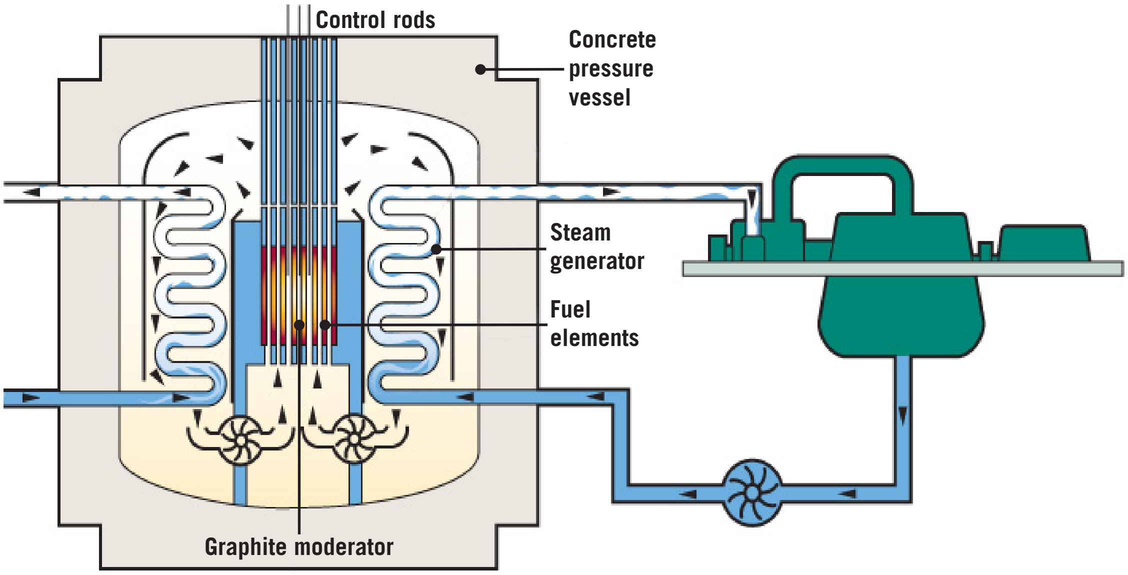


Model of a nuclear reactor showing the control rods

Requirements for a Power Reactor

Fermi's atomic pile, a graphite-moderated thermal reactor using natural uranium, was a very simple affair. The reaction level was kept very low and personnel worked on the exposed pile without protection. To raise the reaction rate to levels where useful amounts of heat are produced safely requires a more complex design:

- In order to control the reaction rate more precisely, a neutron absorbing control material is introduced into the core. The elements boron and cadmium are both suitable and are inserted into steel control rods which can be moved in and out of holes in the core of the reactor to adjust its criticality.
- Some means must be devised for removing the heat from the core. In the case of graphite moderated reactors this is normally done by circulating carbon dioxide gas (CO_2) through the core, since CO_2 has a low neutron absorption. The hot gas can then be passed through a boiler, also known as a heat exchanger, to raise steam. In the case of a heavy water moderated reactor, the heavy water itself can be circulated out of the core and through a heat exchanger to raise steam.
- The whole reactor must be enclosed in a radiation absorbing shield made of lead, steel and concrete, to protect personnel from the very high local levels of radiation that are generated.
- Having generated steam from the nuclear "boiler", the rest of a nuclear power station is similar to a fossil-fuelled power station - the steam being used to drive a turbine, which in turn powers a generator to produce electricity.



Advanced Gas-Cooled Reactor (AGR)

Further Information

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IET nuclear factfile series

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- **Glossary of nuclear terms**
  http://www.theiet.org/factfiles/energy/nuc-terms-page.cfm

Further Reading

- Wood, J. **Nuclear Power**
  (IET Power and Energy Series 52)
  Institution of Engineering and Technology
  (2007) ISBN 0863416683

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