The Basics of Nuclear Energy

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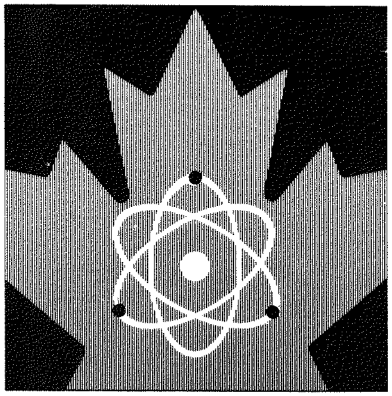
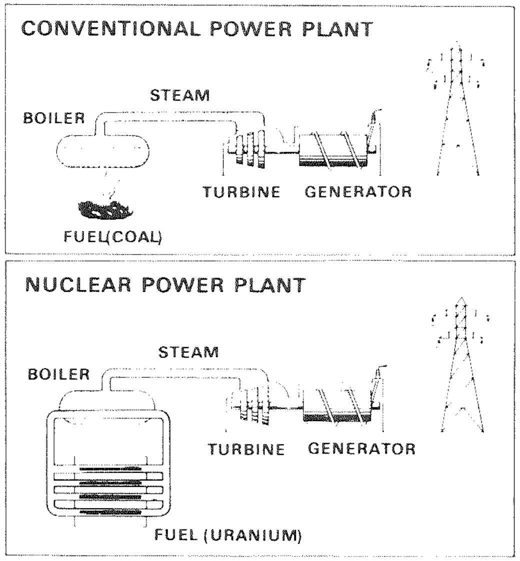


THE BASICS OF NUCLEAR ENERGY

The aim of this pamphlet is to explain some of the terms used in nuclear energy, without relying on a knowledge of nuclear physics. Anyone wanting a simple account of the nuclear physics can find it in the appendix.

In practice, nuclear energy is produced as heat, no different from the heat produced by burning wood, coal or other fuels. In a conventional operating station the heat is used to boil water into steam, which turns a turbine, which drives a generator, producing electricity.



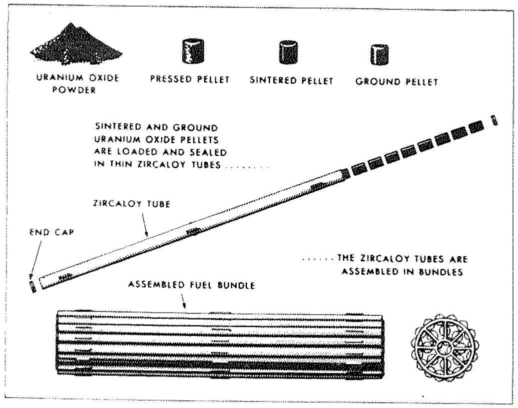
Principles of conventional and nuclear generating stations

In a nuclear generating station the heat is produced by the **fission** of uranium in a **nuclear reactor**, rather than by combustion of fuel in a furnace, but the rest is the same.

Building Blocks

Since the essence of nuclear energy is that it uses uranium as a fuel, let us start with uranium and build a reactor.

Uranium occurs as an ore in the ground and is relatively abundant compared with other minerals. After mining and refining, the uranium is in the form of a yellow powder ("**yellowcake**") and after further chemical treatment a black powder (**uranium dioxide**). To make **fuel pellets**, the uranium dioxide is compacted–as in making aspirin tablets–then fired at high temperatures to yield a hard, insoluble ceramic. A stack of these pellets is loaded into a metal tube, which is sealed at each end by welding, to make a **fuel element**. For current reactors 37 elements are assembled by further welding to form a **fuel bundle**. This fuel bundle is the first basic building block for a **CANDU reactor**, the Canadian design of nuclear reactor for producing useful energy from uranium.



Steps in the fabrication of a uranium fuel bundle for the CANDU nuclear reactor.

Uranium is a very concentrated energy source. A fuel bundle weighs only 22 kg (50 lbs.) and could be carried in an overnight bag. However, just one bundle, when put in a CANDU reactor, can produce as much energy as burning about 400 tons of coal or 2000 barrels of oil. Even when discharged from the reactor it, unlike conventional fuels, is intact and still has the potential to provide much more energy. These facts are important when we consider how to deal with nuclear wastes.

In the reactor these bundles produce heat, which must be removed to the **boiler**. Thus twelve bundles are placed end-to-end in a tube through which water **coolant** is pumped. Since the water is at nearly 300°C (570°F) it develops a pressure about one hundred times the normal atmospheric pressure, and the tubes are known as **pressure tubes**. Each pressure tube with its contained fuel and coolant, and with end-fittings to get the coolant in and out, constitutes a **fuel channel** which is the next larger building block for a CANDU reactor.

Fission, and hence heating, can occur in ordinary (or **natural**) uranium only if three conditions are simultaneously satisfied:

- There must be sufficient uranium present, many megagrams or tons.
- The uranium must be surrounded by a special material, called a **moderator**, in a highly purified form that does not occur naturally.
- The fuel channels must be stacked in a carefully calculated grid.

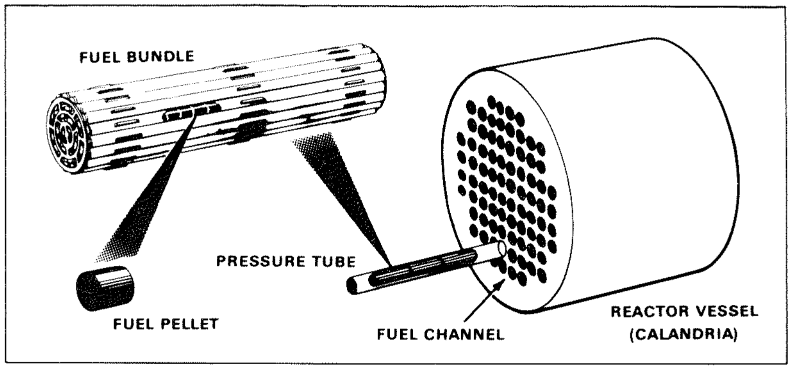
This last condition may seem strange but is quite similar to backyard barbecuing: The briquettes must be separated enough to allow air to get in to sustain combustion, but close enough together for the heat from any one to warm its neighbours.

The same briquettes, if highly purified to form graphite blocks, could be used as a moderator for a nuclear reactor, but **heavy water** is a much better moderator. What is heavy water? The simplest answer is that it is not light, or ordinary, water. Light water, H_2O, is a chemical compound of hydrogen and oxygen. In heavy water the ordinary hydrogen is replaced by **deuterium**, a rare form of hydrogen that is twice as heavy. Heavy water is chemically very similar to light water but is a much better moderator. Heavy water is produced by **enriching** the natural deuterium content of ordinary water in large **heavy water plants**.

The requirement for these three conditions to be satisfied can contribute to the safety of the reactor. If the station were to be seriously damaged, either accidentally or deliberately, one or other of the conditions would probably be affected, hence shutting off the fission process automatically. This is an example of what is known as **fail-safe**.

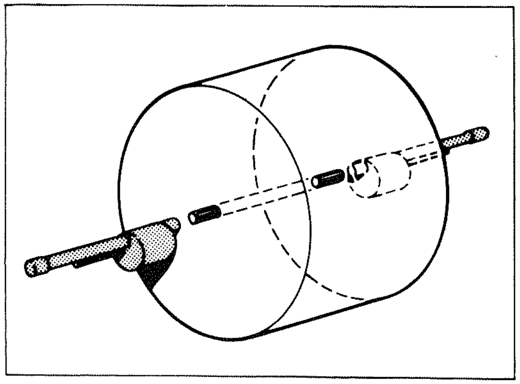
Reactor Design

We now have a **reactor core** consisting of several hundred fuel channels in a large tank of heavy water moderator, called a **calandria**.



Fuel bundle and fuel channel relationship

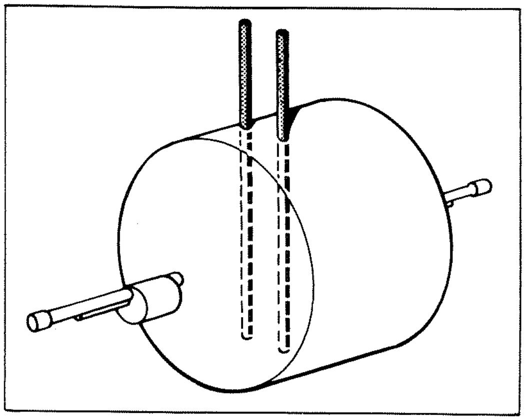
On average, a fuel bundle lasts for one to two years in the reactor. When it needs to be changed, automatically operated **fuelling machines** are clamped to each end of its fuel channel. Fresh fuel is pushed in from one end and the used fuel removed in the machine at the other end. The used fuel bundle looks much the same as the fresh one, and retains all its wastes sealed within it.



Fuelling machines

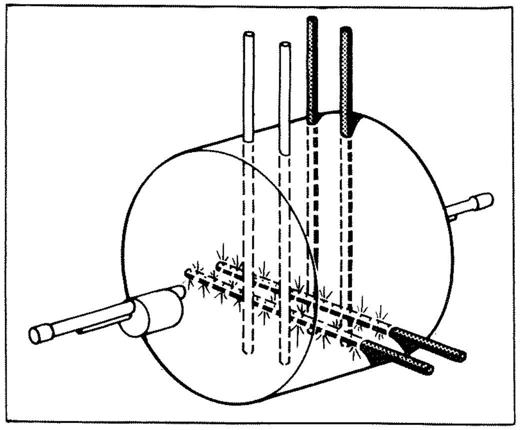
The ability to change fuel for CANDU reactors without having to **shut down** the reactor contributes to their exceptionally high **capacity factors** (the amount of electricity actually generated during some period, expressed as a percentage of what is theoretically possible).

To control the power level of the reactor, in much the same way as the accelerator is used to control the speed of a car, **control rods** are moved into or out of the reactor. For the reactor, unlike the car, the control rods alone can bring things to a stop, i.e., shut down the reactor.



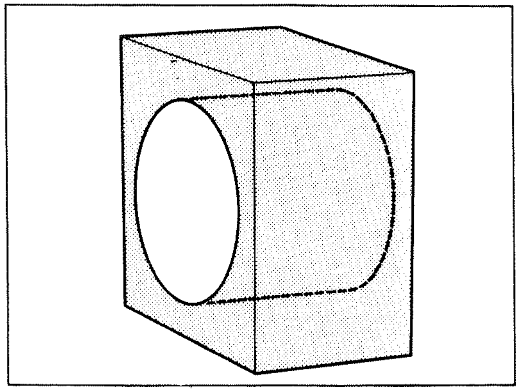
Control rods

To provide extra protection if it is ever needed there are two independent **shutdown systems**, each capable of shutting down the reactor quickly. These can be compared to two independent braking systems in a car, if it is remembered that the shutdown systems, unlike brakes, are neither needed nor used in normal operation; they are there only to take care of unplanned events.



Shutdown systems

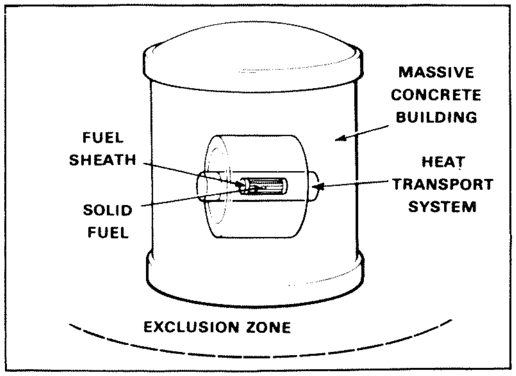
The fuel in an operating reactor (and even when it is discharged) is highly **radioactive**, i.e., it emits radiation similar to medical X-rays. To protect the station operators from this radiation the reactor core is surrounded by heavy **shielding**, typically reinforced concrete about one metre thick.



Shielding

To protect the public against the possibility of **radioactive releases** that might occur in the event of an accident, the whole reactor and its **heat transport system** are located within a sealed **containment**, a massive concrete building.

To provide further protection, there are no dwellings allowed in the immediately surrounding area of about one kilometre radius, the **exclusion zone**.



The principle of "defence in depth"

The use of independent systems such as the shutdown systems, either of which is sufficient, illustrates planned **redundancy**. The combination of all the various safety measures incorporated in a nuclear reactor represent **defence in depth**.

The outstanding performance of CANDU reactors in Ontario, with respect to both safety and capacity factor, has been widely recognized. This proud record is attributable to a combination of sound reactor design by AECL and highly competent operation by the utility, Ontario Hydro.

THE BASICS OF FISSION

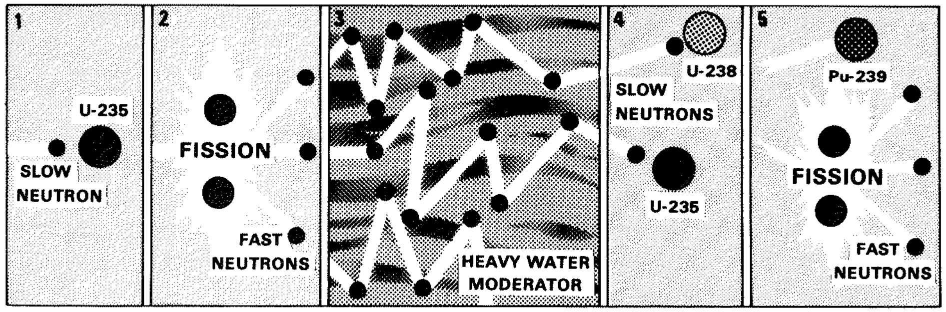
All solids, liquids and gases are composed of less than one hundred different chemical **elements** such as carbon, oxygen, iron and aluminum. The smallest unit of each element that still retains the characteristic properties of that element is an **atom**. Atoms are so small that a single airborne dust particle, that could be seen only under a powerful microscope, contains over a trillion atoms. Hydrogen, the lightest atom, and uranium, the heaviest that exists naturally to any appreciable extent, are both very important to nuclear energy.

Not all atoms of a given element are identical. For instance, hydrogen can exist as three **isotopes**, ordinary hydrogen, **deuterium** and **tritium** with respective masses of one, two and three atomic units. The different isotopes of other elements do not have distinct names but are identified by their masses. Thus the hydrogen isotopes would be hydrogen-1,hydrogen-2 and hydrogen-3. Uranium, as found in nature, consists of 99.28 per cent of uranium-238 and 0.71 per cent of uranium-235, with only very small amounts of other isotopes.

Differences in mass between the isotopes have virtually no effect on the atoms' chemical properties. For example, all three hydrogen isotopes burn in air to form water. Some small differences in common physical properties can be detected, but these are generally of little consequence. A given volume of water produced from deuterium is about ten per cent heavier than the same volume of water from ordinary hydrogen, and is therefore known as **heavy water** compared with the ordinary **light water**. The weight difference between the uranium isotopes is only about one per cent, so that there is little noticeable effect on most physical properties. However, there can be very marked differences between isotopes in their nuclear properties, which determine how they behave in a nuclear reactor.

When an atom of uranium-235 is hit by a **neutron** (a sub-atomic particle that is one of the components of all atoms except hydrogen-1) there is a high probability of a violent reaction, but if the atom is one of uranium-238 the probability is very low. The reaction is known as **nuclear fission** or splitting of the atom, because the uranium atom splits into two lighter atoms, releasing energy. The two light atoms, the **fission products**, can be any one of about twenty atom pairs, such as iodine and silver. The uranium-235 is said to be **fissile** (or **fissionable**).

Two or three neutrons are emitted when an atom fissions. If one of these causes fission in another fissile atom more neutrons are emitted, one of



which could possibly cause a further fission, and so on in a **chain reaction.** If a neutron hits a uranium-238 atom it is unlikely to cause fission. Instead, the two will probably combine and subsequently transform spontaneously into an isotope of another element, plutonium-239. Although uranium-238 is not fissile, plutonium-239 is, so uranium-238 is said to be **fertile**.

However much naturally occurring uranium (**natural uranium**) is heaped up it will not generate useful energy because there are not enough fissile atoms present to sustain a chain reaction. The few neutrons produced are either captured by, or pass through, the much more abundant fertile atoms and so are unavailable to cause further fission.

The brute-force solution to this problem is to increase the proportion of fissile atoms artificially. One way is to **enrich** the uranium in uranium-235 in large **enrichment plants** that exploit the small differences in physical properties between the two uranium isotopes.

A more subtle solution is to divide up the uranium into small packets which are surrounded by a **moderator,** a material that slows down the neutrons, which are travelling very fast when first emitted from a fissioning atom, before they hit the next packet of uranium. The reason that this solution works is that slow neutrons are much more likely to cause fission in uranium-235 than faster ones. Generally, elements with light atoms are good moderators. Ordinary water (a compound of ordinary hydrogen and oxygen) is good, but not good enough to sustain a chain reaction with natural uranium. Very pure graphite (carbon) is better but the best is heavy water (a compound of deuterium and oxygen). Deuterium is present in all naturally occurring hydrogen, e.g., in ordinary water, to the extent of about one part in ten thousand. Heavy water is produced by **enriching** the deuterium content of natural water in large **heavy water plants**.