ADDITIONAL NOTES ON NUCLEAR ENERGY AND POWER PLANTS

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Nuclear Energy – Uranium Isotopes

✓Most chemical elements have several different combinations of protons and neutrons in their nuclei. These naturally occurring combinations are called “isotopes”

✓Power reactors use Uranium as fuel. The naturally occurring isotopes of Uranium are shown below:

$^{234}_{92}\mathrm{U}$

92 Protons
142 Neutrons

$^{235}_{92}\mathrm{U}$

92 Protons
143 Neutrons

$^{238}_{92}\mathrm{U}$

92 Protons
146 Neutrons

Nuclear Energy – The Uranium

- ✓ **Uranium found in nature consists largely of two isotopes, U-235 and U-238. Natural raw Uranium contains about 99.3% of the U-238 isotope, which does not contribute to the fission process. It only contains 0.7% of the U-235 isotope which is fissionable**
- ✓ **The production of energy in nuclear reactors is from the 'fission' or splitting of the U-235 atoms.**
- ✓**Most reactors are Light Water Reactors and require the uranium to be enriched from 0.7% to 3% - 5% U-235 in their fuel**

Nuclear Energy – Uranium Enrichment

Uranium enrichment is the process of isotope separation. Enrichment, is a physical process to concentrate (enrich) one isotope relative to the others. Two enrichment methods are commercially used, they are:

- **the gaseous diffusion process**
- **the centrifuge process**

Nuclear Energy – Uranium Enrichment

In both of these processes, UF_6 (Uranium Hexafluoride) gas is used as the feed material. Molecules of UF_6 with U-235 atoms are about one percent lighter than the rest, and this difference in mass is the basis of both processes. Isotope separation is a physical process.

Nuclear Energy – The Uranium Enrichment

The slide on the left shows the row naturally found Uranium Ore.
The slide on the right shows the enriched Uranium when it is make as "Fuel Pellet" before insertion in reactors.

Uranium Ore (0.7%)

Fuel Pellet (3.5%)

Nuclear Energy – The Uranium

- ☐ Uranium-235 and U-238 are chemically identical, but differ in their physical properties, notably their mass.
- ☐ The nucleus of the U-235 atom contains 92 protons and 143 neutrons, giving an atomic mass of 235 units. The U-238 nucleus also has 92 protons but has 146 neutrons - three more than U-235, and therefore has a mass of 238 units.

Nuclear Power Stations – The Fission Process

- **When a nucleus fissions, it splits into several smaller fragments. Two or three neutrons are also emitted. Fission can occur when a nucleus of a heavy atom captures a neutron, or it can happen spontaneously**

- **$U^{235} + n \rightarrow \text{fission} + 2 \text{ or } 3\ n + 200\ \text{MeV}$**

- **The sum of the masses of these fragments is less than the original mass. This 'missing' mass (about 0.1 % of the original mass) has been converted into energy according to Einstein's equation.**

Einstein's energy-mass equivalence equation

One of the most extraordinary things about Einstein's energy-mass equivalence equation is its simplicity. The equation states the following:

$$\mathbf{E = mc^2}$$

Where:

E = energy (joules)
m = mass (kilograms)
c = the speed of light ($3 \times 10^8\ ms^{-1}$)

Solving Einstein's Equation

Calculate the amount of energy released when a mass of 1kg is completely converted into energy:

$$
\begin{aligned}
E &= mc^2 \\
&= 1\text{kg} \times \left(3\times10^{8}\,\text{ms}^{-1}\right)^{2} \\
&= 1\text{kg} \times \left(3\times10^{8}\,\text{ms}^{-1}\right)\times\left(3\times10^{8}\,\text{ms}^{-1}\right) \\
&= 1\text{kg} \times \left(9\times10^{16}\,\text{m}^{2}\text{s}^{-2}\right) \\
&= 1\times\left(9\times10^{16}\right)\text{kg m}^{2}\text{s}^{-2} \\
&= 9\times10^{16}\,\text{J}
\end{aligned}
$$

So from 1kg of matter, *any* matter, we get:

90,000,000,000,000,000 joules

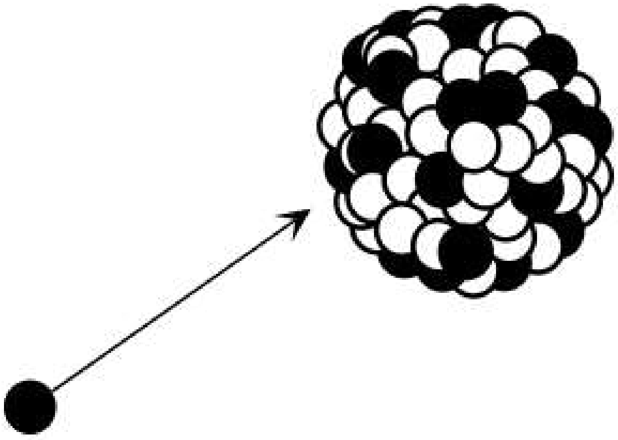
Nuclear Power Stations – The Fission Process

Uranium-235 is used as a reactor fuel because:

1) It will readily absorb a neutron to become the highly unstable isotope U-236.

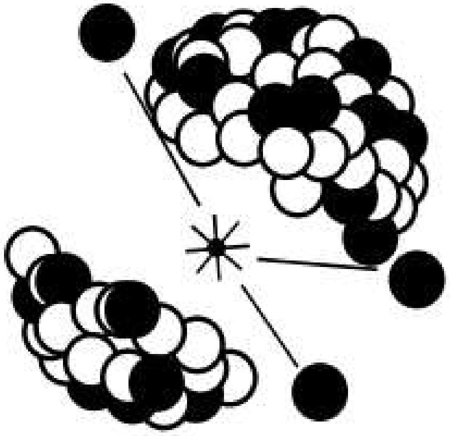
2) U-236 has a high probability of fission (about 80% of all U-236 atoms will fission) and releases energy (in the form of heat) which is used to produce high pressure steam and ultimately electricity.

4) The fission also releases two or three additional neutrons which can be used to cause other fissions and establish a "chain reaction."

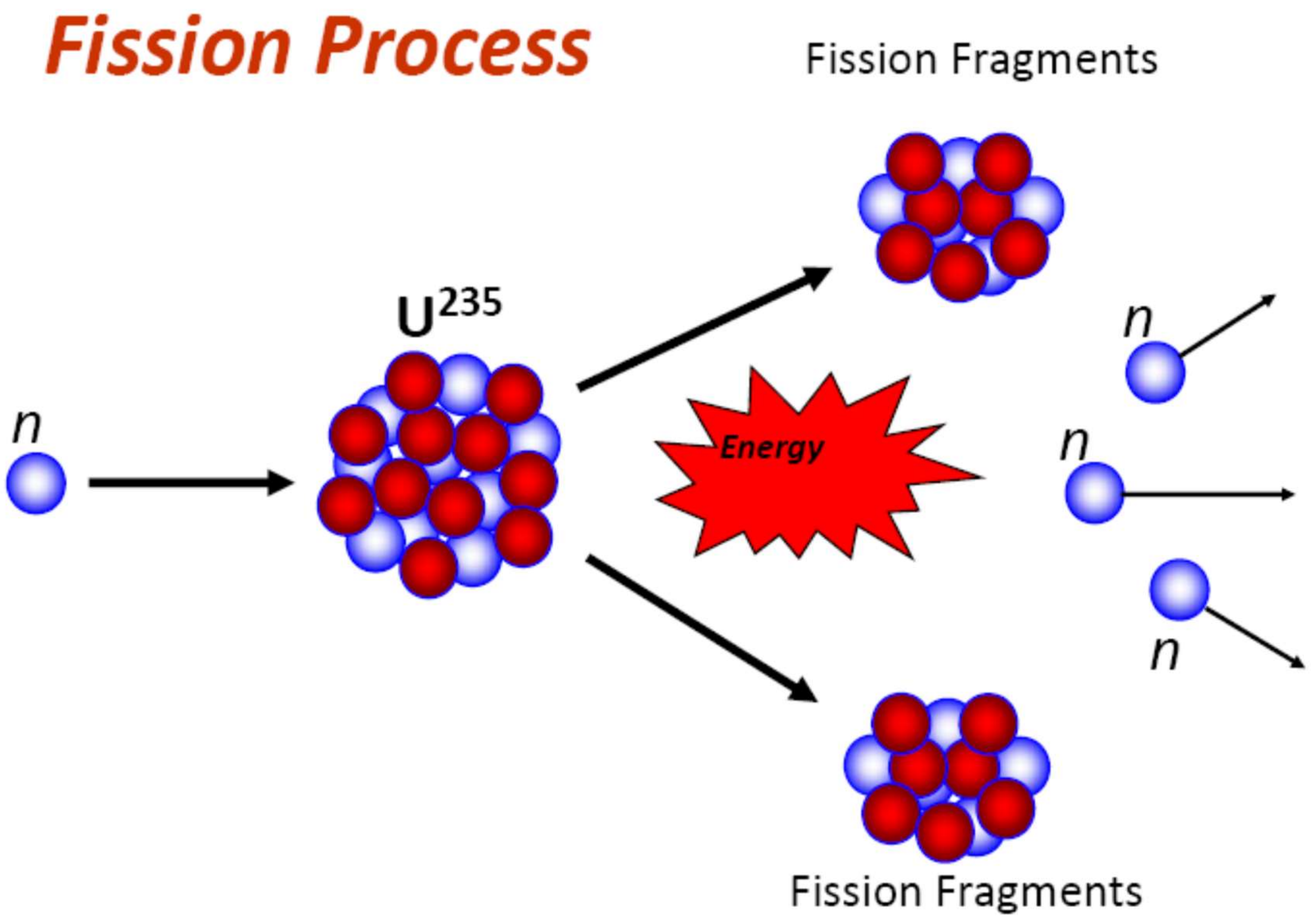


Absorption

Fission



Nuclear Power Stations – The Fission Process



Nuclear Power Stations – The Fission Process

- **Although two to three neutrons are produced for every fission, not all of these neutrons are available for continuing the fission reaction.**
- **If the conditions are such that the neutrons are lost at a faster rate than they are formed by fission, the chain reaction will not be self-sustaining.**
- **At the point where the chain reaction can become self-sustaining, this is referred to as critical mass**

Nuclear Power Stations – The Chain Reaction

- A chain reaction is a process in which neutrons released in fission produce an additional fission in at least one further nucleus.
- This nucleus in turn produces neutrons, and the process is repeated.
- The process may be controlled (nuclear power) or uncontrolled (nuclear weapons)

Nuclear Power Stations – Nuclear Recator

A Nuclear reactor is a device that initiate and control a sustained nuclear chain reaction.

Nuclear reactors are used at nuclear power plants for generating heat and, therefore, electricity. Heat from nuclear fission is passed to a working fluid (water or gas), which changes into steam and turn turbines. Fuel, made up of heavy atoms that split when they absorb neutrons, is placed into the reactor vessel (basically a large tank) along with a neutron source.

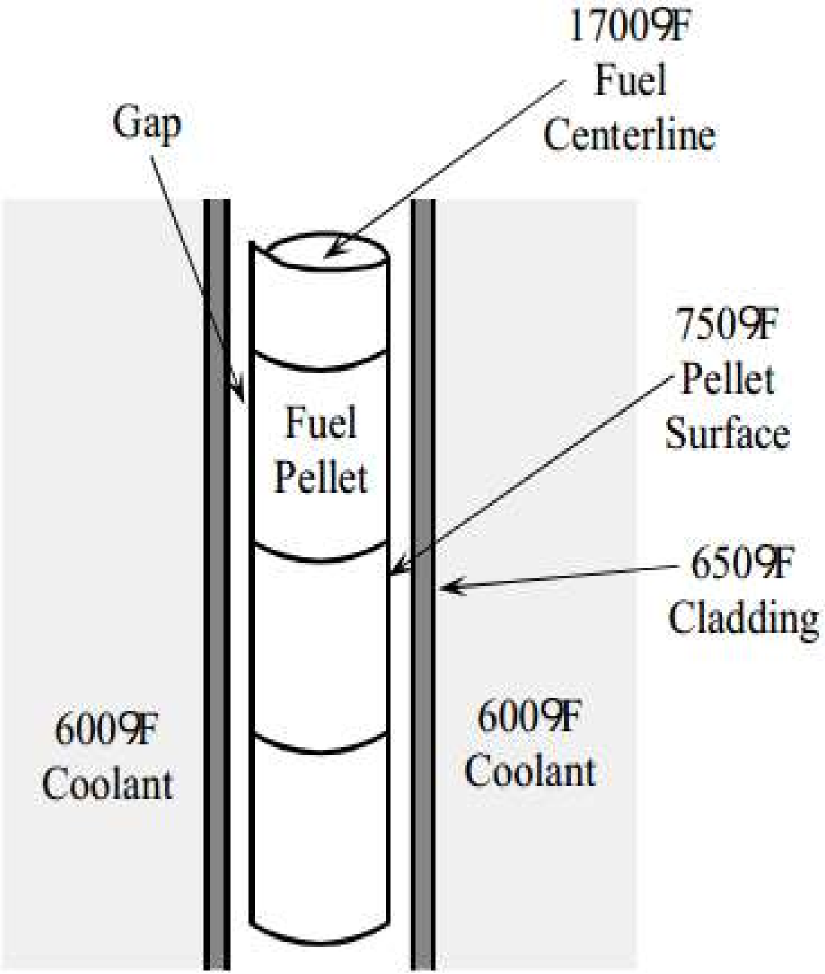
Nuclear Reactor – The Main Components

The main components of a Nuclear Reactor are:

- ☐ ***The core*** **of the reactor, which contains all of the nuclear fuel and generates all of the heat. It contains low-enriched Uranium (<5% U-235), control systems and structural materials. The core can contain hundreds of thousands of individual fuel pins.**
- ☐ ***The coolant*** **is the material that passes through the core, transferring the heat from the fuel to a turbine. It could be water, heavy-water, liquid sodium, helium, or something else.**
- ☐ ***The containment*** **is the structure that separates the reactor from the environment. These are usually dome-shaped, made of high-density, steel-reinforced concrete. Chernobyl did not have a containment to speak of.**

The Conditions Inside a Nuclear Reactor

When a reactor is operating at full power, the approximate temperatures of the fuel centerline, pellet surface, cladding surface, and coolant are shown. The average fuel pellet temperature under normal operating conditions is about 1400F (760 Deg.C.).



The Conditions Inside a Nuclear Reactor

The melting temperature of the ceramic fuel is about 5200F (2870 deg. C.). The fuel cladding can be damaged by temperatures in excess of 1800F (980 deg.C.). Significant fuel damage can be expected at sustained temperatures above 2200F (1200 deg. C.). The plant systems, both normal operating and emergency, must be designed to maintain the fuel temperature low enough to prevent fuel damage. For example, if conditions approach an operating limit, the reactor protection system will rapidly insert the control rods to shut down the fission process, which removes a major heat production source. This rapid insertion of rods into the core is called a reactor trip or scram.

Nuclear Reactor Components

Control Rods:

Control rods play a vital role in the control of the energy generated in a nuclear reactor. Their role is to absorb the access neutrons in the reactor, and therefore slows down or even stops the fission process.

This needs to be done when no electrical energy is needed or in case of emergency. To maintain a sustained controlled nuclear reaction, for every 2 or 3 neutrons released, only one must be allowed to strike another uranium nucleus.

Nuclear Reactor Components

- If this ratio is less than 1, the reaction will die out; if it is greater than one it will grow uncontrolled (an atomic explosion).
- A neutron absorbing element must therefore be present to control the amount of free neutrons in the reaction space. Such an element is called a control rod.
- Most reactors are controlled by means of control rods that are made of a strongly neutron-absorbent material such as boron or cadmium.

Nuclear Reactor Components

Properties of the Control Rods:

- **One property which is a must for control rod material is the heavy absorption capacity for neutrons so that they can carry out the control function effectively.**
- **Another property of control rods is that the rod material should not start a fission reaction despite the heavy absorption of neutrons.**

Nuclear Reactor Components

The Moderator:

In addition to the need to *capture* neutrons, the neutrons often have too much kinetic energy. These *fast neutrons* are slowed down through the use of a moderator such as heavy water and ordinary water.

Some reactors use graphite as a moderator, but this design has problems. Once the fast neutrons have been slowed down, they are more likely to produce further nuclear fissions or be absorbed by the control rod.

LIGHT WATER REACTORS (LWR)

Many different types of Nuclear Reactors have been developed that use gas (carbon dioxide, for example). However, by moving to higher level of Uranium enrichment, it is possible to tolerate greater level of neutron absorption in the core if ordinary water is used as a moderator and as a coolant. The class of nuclear reactors that use ordinary water are called Light Weight Water Reactors.

LIGHT WATER REACTORS (LWR)

The family of nuclear reactors known as light water reactors (LWR), cooled and moderated using ordinary water, tend to be simpler and cheaper to build than other types of nuclear reactor, and are well known to have excellent safety and stability characteristics.

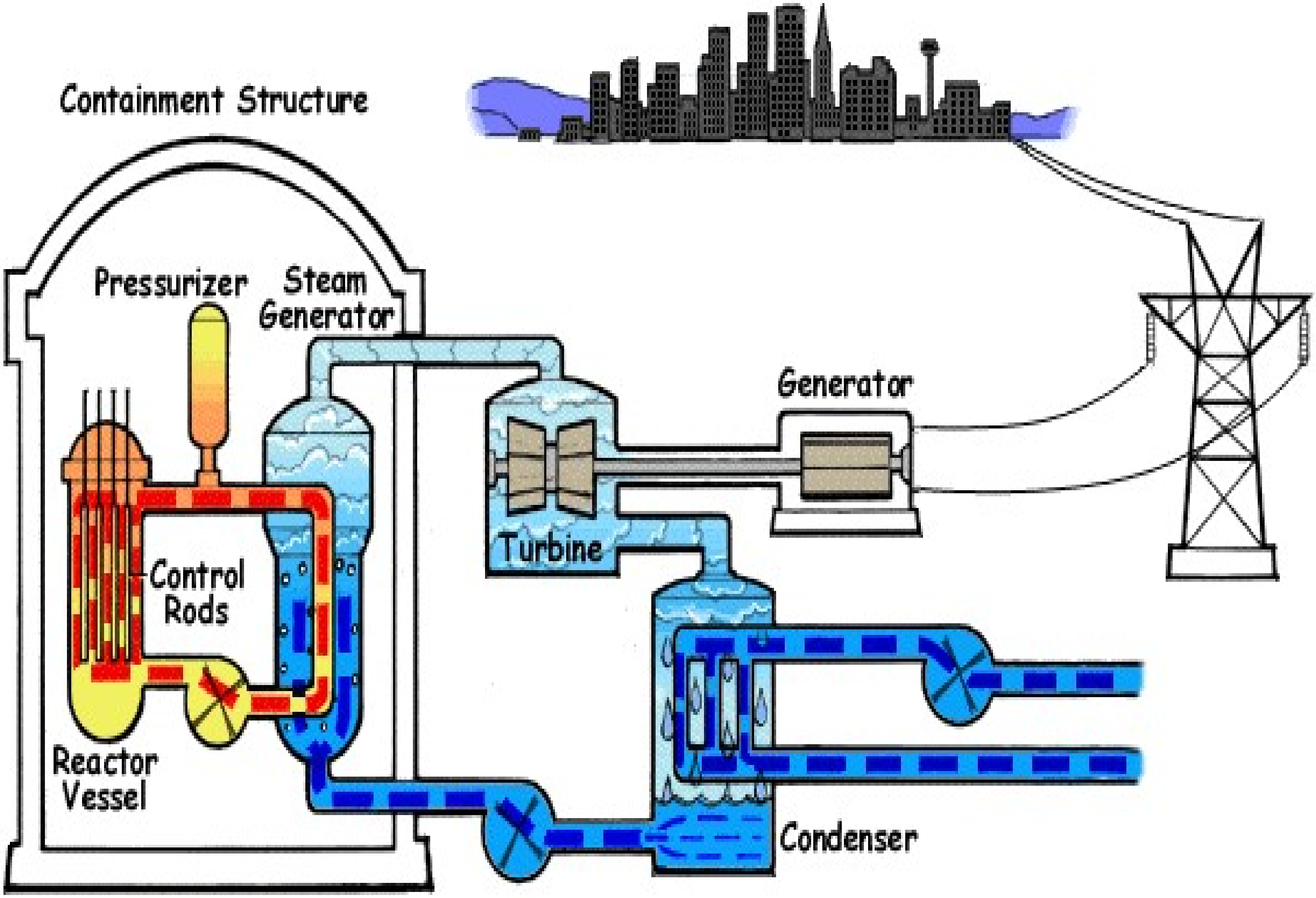
Due to these factors, they make up the vast majority of civil nuclear reactors in service throughout the world. LWRs can be subdivided into the following categories:

- **Pressurized water reactors (PWRs),**
- **Boiling water reactors (BWRs), and**

THE PRESSURIZED WATER REACTOR (PWR)

- ☐ A pressurized-water reactor (PWR) uses ordinary water as the reactor coolant and moderator in the state of high temperature and high pressure
- ☐ The water does not boil in the reactor core (primary system: reactor coolant system) but is sent as high-temperature and high-pressure water to steam generators (primary system) to generate steam with heat exchangers (steam system: secondary coolant system)
- ☐ A steam turbine generator is then used to generate electricity.

Pressurized Water Reactor – Block Diagram



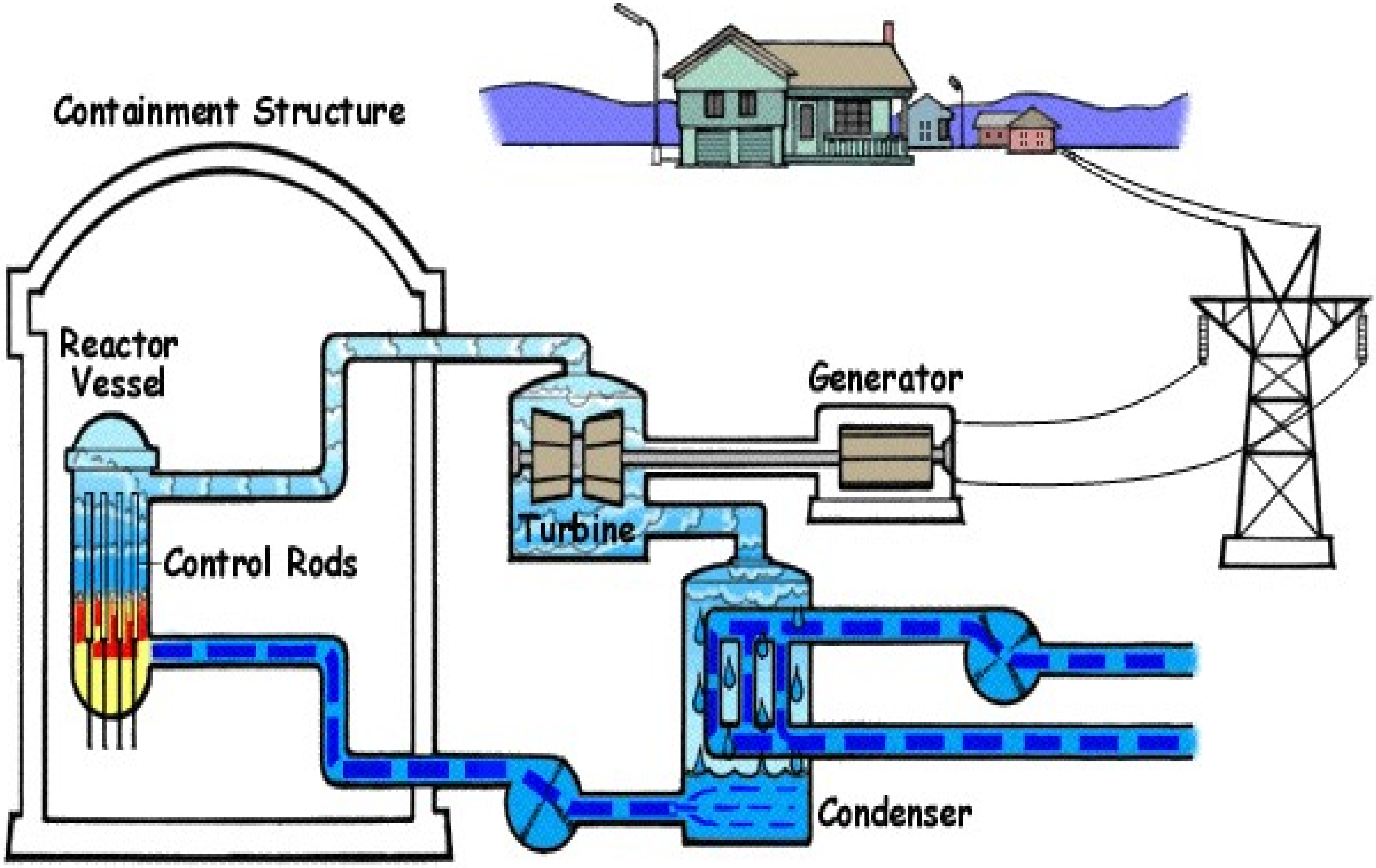
Courtesy of Wikipidia

The Boiling Water Reactor

The second type of water cooled and moderated reactor does away with the steam generator (boiler) and, by allowing the water within the reactor circuit to boil, it generates steam directly for electrical power generation. This, however, leads to some radioactive contamination of the steam circuit and turbine, which then requires shielding of these components in addition to that surrounding the reactor. Such reactors, known as Boiling Water Reactors (BWRs), (see next slide) are in use in some ten countries throughout the world.

Courtesy of Wikipidia

The Boiling Water Reactor – Block Diagram



Source: Wikipidia