How Do Nuclear Plants Work?

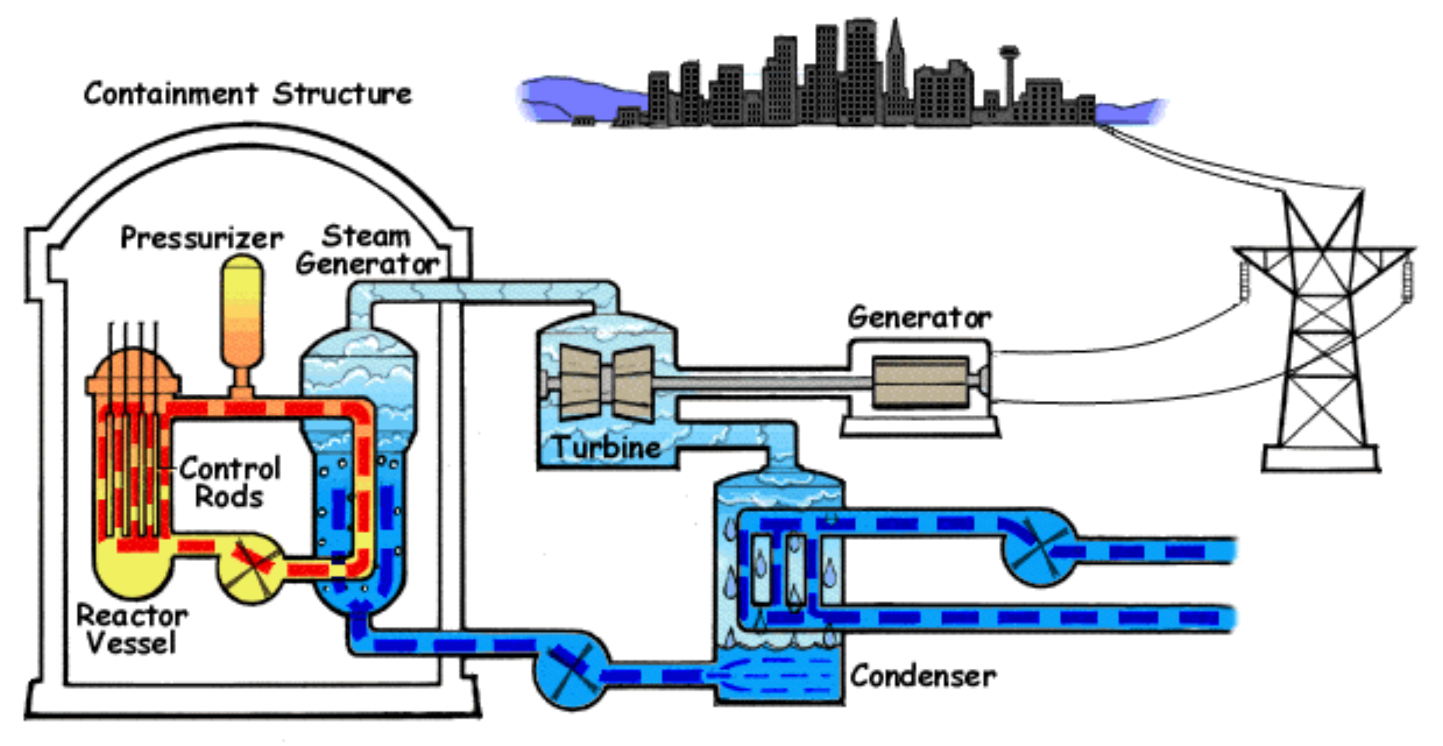
In a nuclear-fueled power plant – much like a fossil-fueled power plant – water is turned into steam, which in turn drives turbine generators to produce electricity.

- Source of heat: Nuclear Fission (no combustion in the nuclear reactor)

2 types of nuclear reactors (in the US):

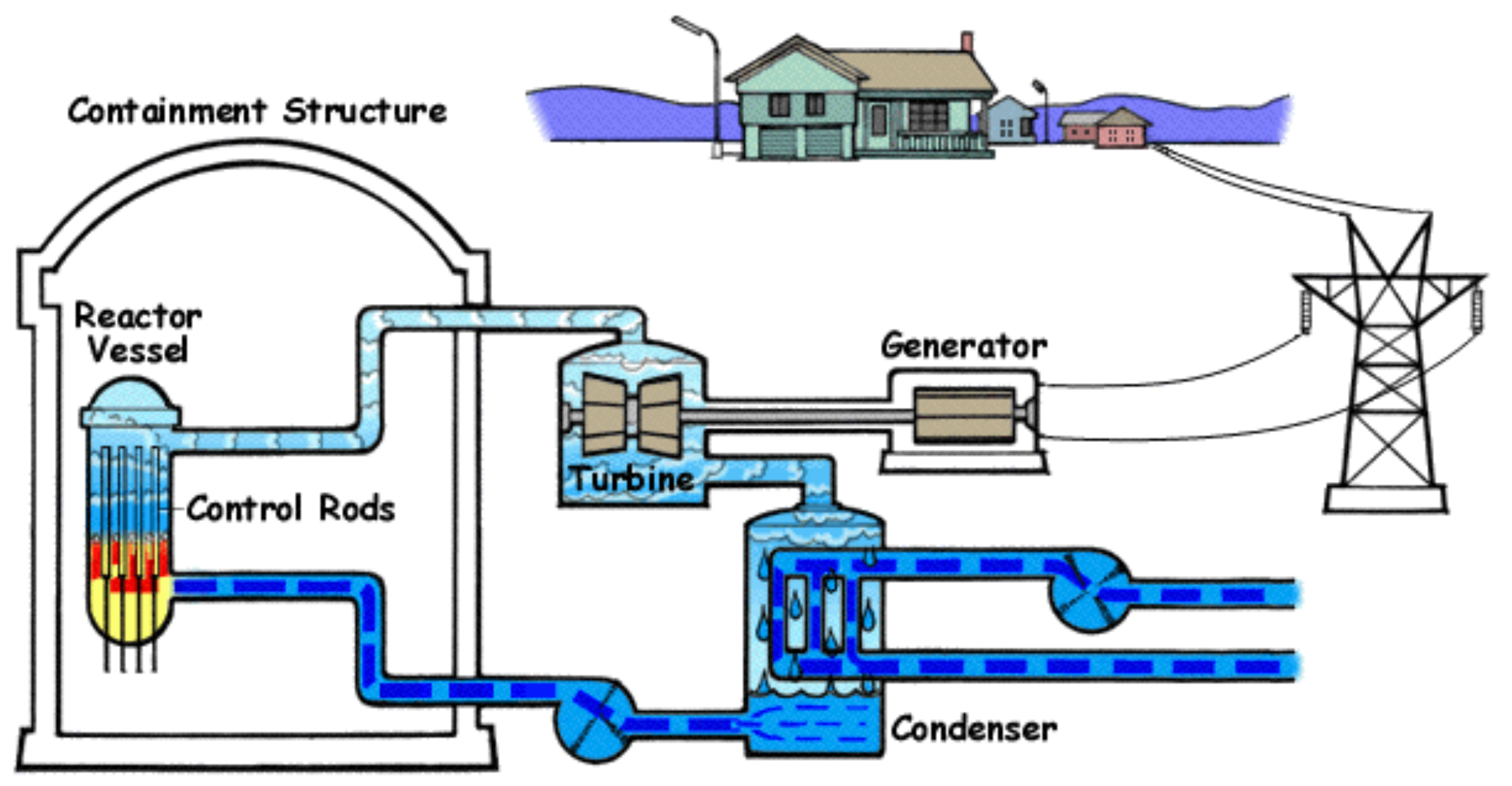
1. Pressurized Water Reactor (about 85% of the total)

Pressurized Water Reactors (also known as PWRs) keep water under pressure (at >300°C) so that it heats, **but does not boil**. This heated water is circulated through tubes in steam generators, allowing the water in the steam generators to turn to steam, which then turns the turbine generator. Water from the reactor and the water that is turned into steam are in separate systems and do not mix.



2. Boiling Water Reactor

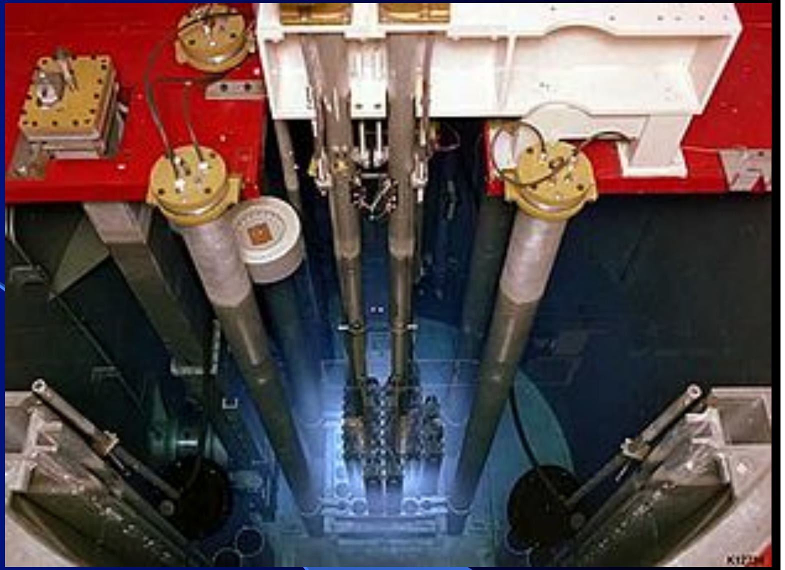
In Boiling Water Reactors (also known as BWRs), the water heated by fission actually boils and turns into steam to turn the turbine generator. In both PWRs and BWRs, the steam is turned back into water and can be used again in the process.



Other applications:

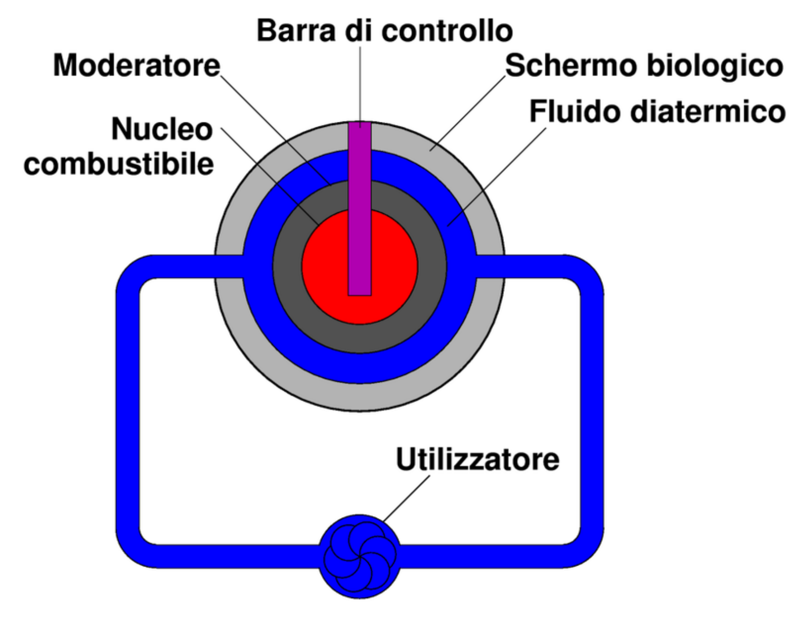
- In a **research reactor** the main purpose is to utilise the actual neutrons produced in the core.
- In most **naval reactors**, steam drives a turbine directly for propulsion.

Centrali nucleari.



La struttura di un reattore nucleare deve quindi prevedere schematicamente:

- **Un nocciolo**, nel quale si sviluppi la reazione a catena (con una massa critica di combustibile tale che la reazione si autosostenga.
- **Un moderatore** della reazione spesso anche con funzione di refrigerante, che rallenta i neutroni in modo che abbiano la velocità corretta per la fissione.
- un efficientissimo sistema di estrazione del calore (raffreddamento) dal nocciolo
- una **schermatura** per fermare le radiazioni prodotte in modo ineliminabile dal processo di fissione;
- Sistemi di regolazione del processo: **barre di controllo** (in genere leghe di argento, cadmio e indio o carburi di boro) che vengono inserite nel nocciolo. Queste vengono calate ad altezza variabile tra le varie barre di combustibile, per rallentare o accelerare la fissione e quindi regolare la potenza del reattore.



Components of a nuclear reactor

(http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Nuclear-Power-Reactors/)

There are several components common to most types of reactors:

1. Fuel.

Uranium is the basic fuel. Usually pellets of uranium oxide (UO_2) are arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core.

- In a new reactor with new fuel a neutron source is needed to get the reaction going. Usually this is **beryllium** mixed with **polonium, radium** or other **alpha-emitter.** Alpha particles from the decay cause a release of neutrons from the beryllium as it turns to carbon-12.
- The reaction is: $^{9}\mathrm{Be}(\alpha, n)^{12}\mathrm{C}$
- Restarting a reactor with some used fuel may not require this, as there may be enough neutrons to achieve criticality when control rods are removed.

Il combustibile

Fissionabile = che può subire fissione
fissile = che può sviluppare una reazione a catena con neutroni lenti

- **Uranio**:
  - ^{238}U → fissionabile ma non fissile (può contribuire alla reazione ma non raggiunge la "massa critica da solo") → FERTILE
  - ^{235}U → fissile = che può sviluppare una reazione a catena con neutroni lenti se bombardato da neutroni (lenti)
  - L'Uranio naturale (circa 0.7% ^{235}U) non riesce a raggiungere la criticità, quindi si usa di solito U arricchito in ^{235}U (fino al 5%)

Perché uno sì e l'altro no.

^{235}U undergoes fission with low-energy thermal neutrons because the binding energy (energia di legame) resulting from the absorption of a neutron is greater than the critical energy required for fission; therefore ^{235}U is a fissile material. By contrast, the binding energy released by ^{238}U absorbing a thermal neutron is less than the critical energy, so the neutron must possess additional energy for fission to be possible. Consequently, ^{238}U is a fissionable material but not a fissile material

- **Plutonio:**
  - ^{244}Pu (+stabile: $t_{1/2}$ = 80My),
  - ^{242}Pu ($t_{1/2}$ = 373ky)
  - ^{239}Pu ($t_{1/2}$ = 23ky)
  - ^{239}Pu → principale prodotto fissile per armi nucleari,
  - prodotto nei reattori nucleari per cattura neutronica da $^{238}U \rightarrow ^{239}U$ che poi decade (beta) a ^{239}Np e ^{239}Pu (*fertilizzazione*). I reattori funzionano principalmente con ^{235}U, ma le barre contengono (ovviamente) anche una grande quantità di ^{238}U che cattura i neutroni formando Pu in pratica come prodotto di scarto.
  - Per ulteriore cattura neutronica $^{239}Pu \rightarrow ^{240}Pu$ superfissile (10000volte + probabilità di ^{239}Pu) e non controllabile.
- Weapon grade: 90% ^{239}Pu
- Nei normali reattori commerciali si ottiene un Pu con circa 20% di ^{240}Pu

Components of a nuclear reactor

2. Moderator

Material in the core which slows down the neutrons released from fission so that they cause more fission. *(per quanto possa sembrare strano, infatti, i neutroni lenti sono molto pi ù efficaci di quelli veloci nell'innescare la fissione).* It is usually water, but may be heavy water or graphite

U238 (99.283%) and U235 (0.711%). The former is not fissionable while the latter can be fissioned by thermal (i.e. slow) neutrons. As the neutrons emitted in a fission reaction are fast, reactors using U235 as fuel must have a means of slowing down these neutrons before they escape from the fuel. This function is performed by what is called a moderator, which, in the case of certain reactors simultaneously acts as a coolant.

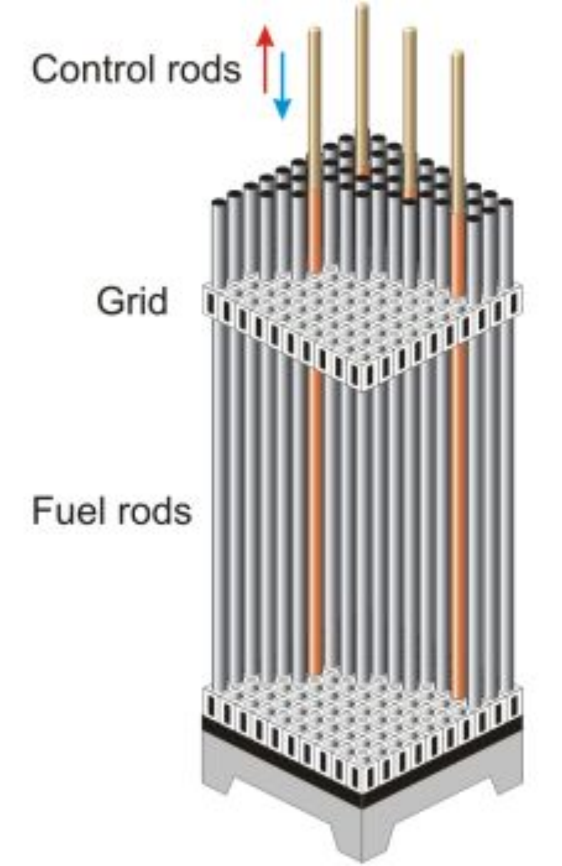
Moderation provided by light water is not sufficiently effective to permit the use of natural uranium. The fuel must be slightly enriched in U235 to make up for the losses of neutrons occurring during the chain reaction. On the other hand, heavy water is such an effective moderator that the chain reaction can be sustained without having to enrich the uranium. This combination of natural uranium and heavy water is used in PHWRs, which are found in a number of countries, including Canada, Korea, Romania and India.

Components of a nuclear reactor

3. Control rods.

These are made with **neutron-absorbing material** such as cadmium, hafnium or boron, and are inserted or withdrawn from the core **to control the rate of reaction, or to halt it.*** In some PWR reactors, special control rods are used to enable the core to sustain a low level of power efficiently. (Secondary control systems involve other neutron absorbers, usually boron in the coolant - its concentration can be adjusted over time as the fuel burns up.)

* In fission, most of the neutrons are released promptly, but some are delayed. These are crucial in enabling a chain reacting system (or reactor) to be controllable and to be able to be held precisely critical.



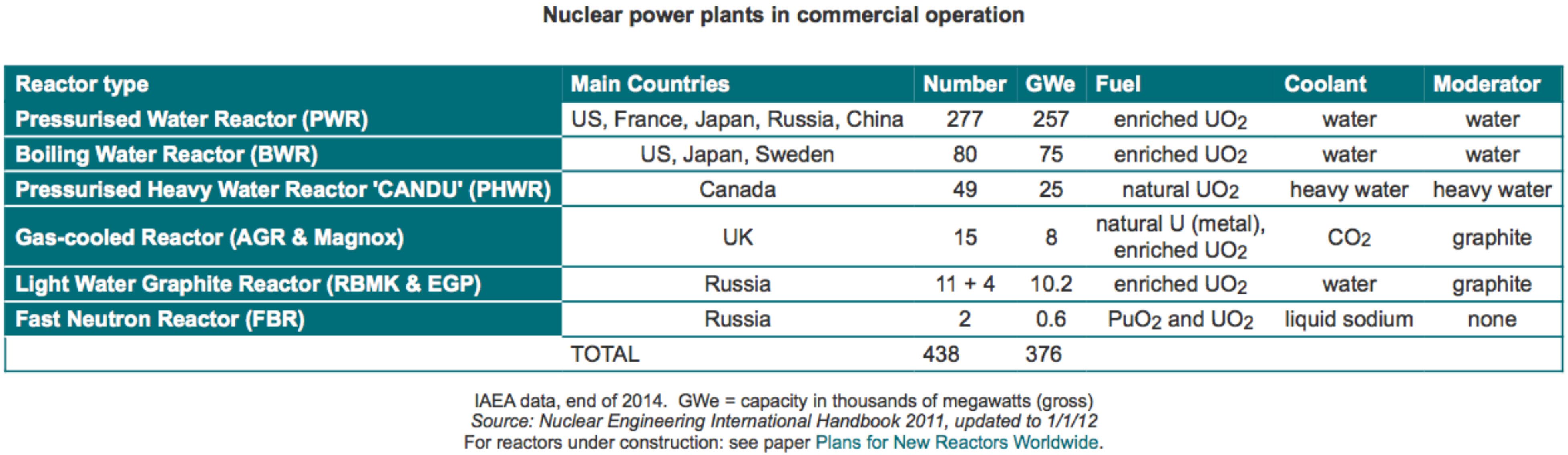
Components of a nuclear reactor

4. Coolant. A fluid circulating through the core so as to transfer the heat from it. In light water reactors the water moderator functions also as primary coolant. Except in BWRs, there is secondary coolant circuit where the water becomes steam. (See also later section on primary coolant characteristics)

5. Pressure vessel or pressure tubes. Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the surrounding moderator.

6. Steam generator. Part of the cooling system of pressurised water reactors (PWR & PHWR) where the high-pressure primary coolant bringing heat from the reactor is used to make steam for the turbine, in a secondary circuit.

7. Containment. The structure around the reactor and associated steam generators which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any serious malfunction inside. It is typically a metre-thick concrete and steel structure.



Nuclear power plants in commercial operation

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia, China	277	257	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	80	75	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	49	25	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	15	8	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK & EGP)	Russia	11 + 4	10.2	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Russia	2	0.6	PuO_2 and UO_2	liquid sodium	none
	TOTAL	438	376			

IAEA data, end of 2014. GWe = capacity in thousands of megawatts (gross)
Source: Nuclear Engineering International Handbook 2011, updated to 1/1/12
For reactors under construction: see paper Plans for New Reactors Worldwide.

- If graphite or heavy water is used as moderator, it is possible to run a power reactor on natural U instead of enriched uranium. Natural uranium has the same elemental composition as when it was mined (0.7% U-235, over 99.2% U-238).
- → During operation, some of the U-238 is changed to plutonium, and Pu-239 ends up providing about one third of the energy from the fuel. Heavy water is a more efficient moderator than grafite

- Enriched uranium has had the proportion of the fissile isotope (U-235) increased by a process called enrichment, commonly to 3.5 - 5.0%. In this case the moderator can be ordinary water, and such reactors are collectively called light water reactors. Because the light water absorbs neutrons as well as slowing them, it is less efficient as a moderator than heavy water or graphite.

Nuclear fuel cycle

Thermal reactors generally depend on refined and enriched uranium. Some nuclear reactors can operate with a mixture of plutonium and uranium (MOX). The process by which uranium ore is mined, processed, enriched, used, possibly reprocessed and disposed of is known as the nuclear fuel cycle.

Under 1% of the uranium found in nature is the easily fissionable U-235 isotope and as a result most reactor designs require enriched fuel. Enrichment involves increasing the percentage of U-235 and is usually done by means of gaseous diffusion or gas centrifuge. The enriched result is then converted into uranium dioxide powder, which is pressed and fired into pellet form. These pellets are stacked into tubes which are then sealed and called fuel rods. Many of these fuel rods are used in each nuclear reactor.

Most BWR and PWR commercial reactors use uranium enriched to about 4% U-235.

Some commercial reactors with a high neutron economy do not require the fuel to be enriched at all (that is, they can use natural uranium).

Fissile U-235 and non-fissile but fissionable and fertile U-238 are both used in the fission process.

U-235 is fissionable by thermal (i.e. slow-moving) neutrons

U-238 is more likely to capture a neutron when the neutron is moving very fast. This U-239 atom will soon decay into plutonium-239, which is another fuel. Pu-239 is a viable fuel and must be accounted for even when a highly enriched uranium fuel is used. Plutonium fissions will dominate the U-235 fissions in some reactors, especially after the initial loading of U-235 is spent. Plutonium is fissionable with both fast and thermal neutrons, which make it ideal for either nuclear reactors or nuclear bombs.

Most reactor designs in existence are thermal reactors and typically use water as a neutron moderator (moderator means that it slows down the neutron to a thermal speed) and as a coolant.

But in a fast breeder reactor, some other kind of coolant is used which will not moderate or slow the neutrons down much. This enables fast neutrons to dominate, which can effectively be used to constantly replenish the fuel supply. By merely placing cheap unenriched uranium into such a core, the non-fissionable U-238 will be turned into Pu-239, "breeding" fuel.

In thorium fuel cycle thorium-232 absorbs a neutron in either a fast or thermal reactor. The thorium-233 beta decays to protactinium-233 and then to uranium-233, which in turn is used as fuel. Hence, like uranium-238, thorium-232 is a fertile material.

Fueling of nuclear reactors

The amount of energy in the reservoir of nuclear fuel is frequently expressed in terms of "full-power days," which is the number of 24-hour periods (days) a reactor is scheduled for operation at full power output for the generation of heat energy.

The number of full-power days in a reactor's operating cycle (between refueling outage times) is related to the amount of fissile uranium-235 (U-235) contained in the fuel assemblies at the beginning of the cycle. A higher percentage of U-235 in the core at the beginning of a cycle will permit the reactor to be run for a greater number of full-power days.

At the end of the operating cycle, the fuel in some of the assemblies is "spent" and is discharged and replaced with new (fresh) fuel assemblies, although in practice it is the buildup of reaction poisons in nuclear fuel that determines the lifetime of nuclear fuel in a reactor.

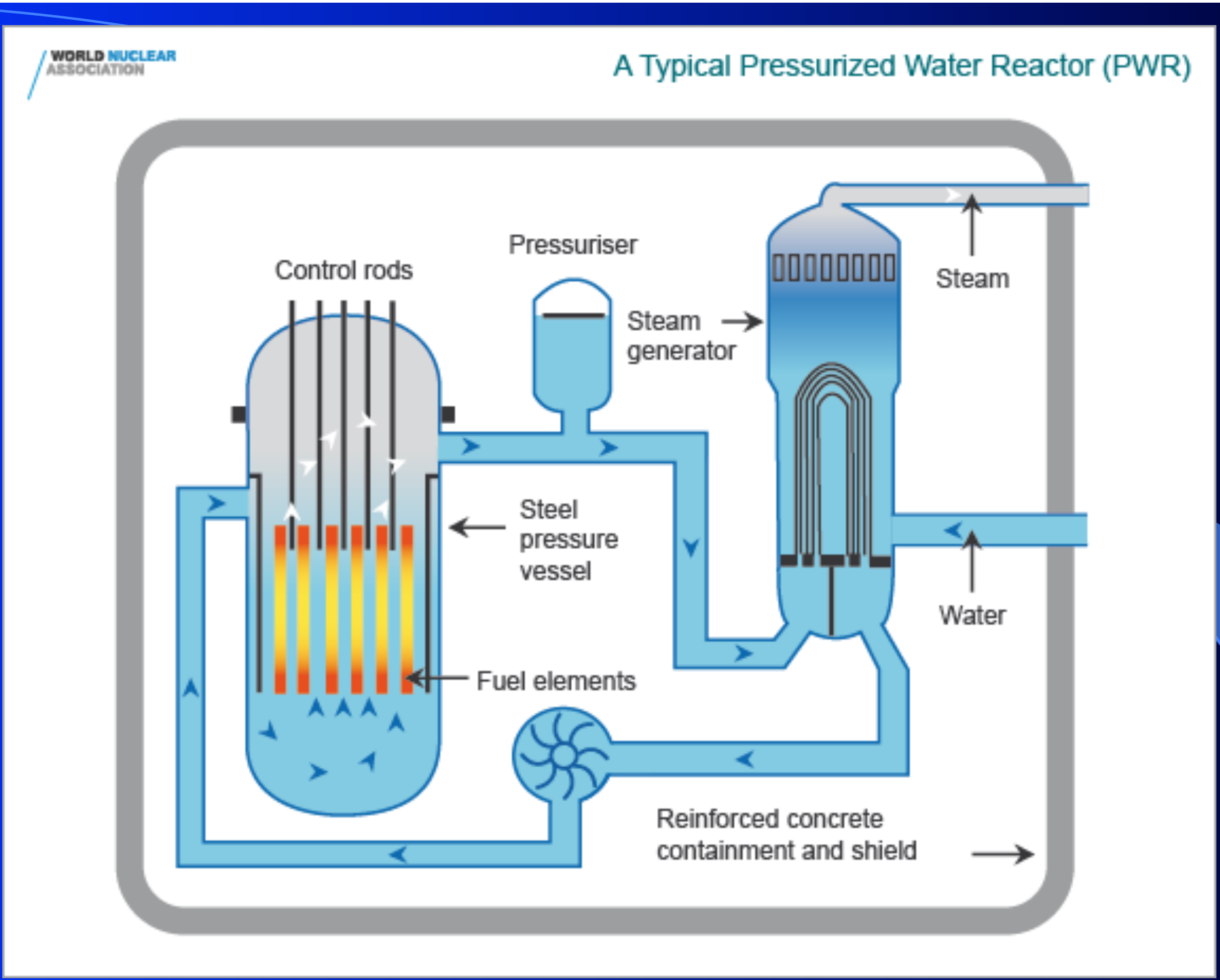
Fueling of nuclear reactors

.. Long before all possible fission has taken place, the buildup of long-lived neutron absorbing fission byproducts impedes the chain reaction.

The fraction of the reactor's fuel core replaced during refueling is typically one-fourth for a boiling-water reactor and one-third for a pressurized-water reactor.

The disposition and storage of this spent fuel is one of the most challenging aspects of the operation of a commercial nuclear power plant. This nuclear waste is highly radioactive and its toxicity presents a danger for thousands of years.

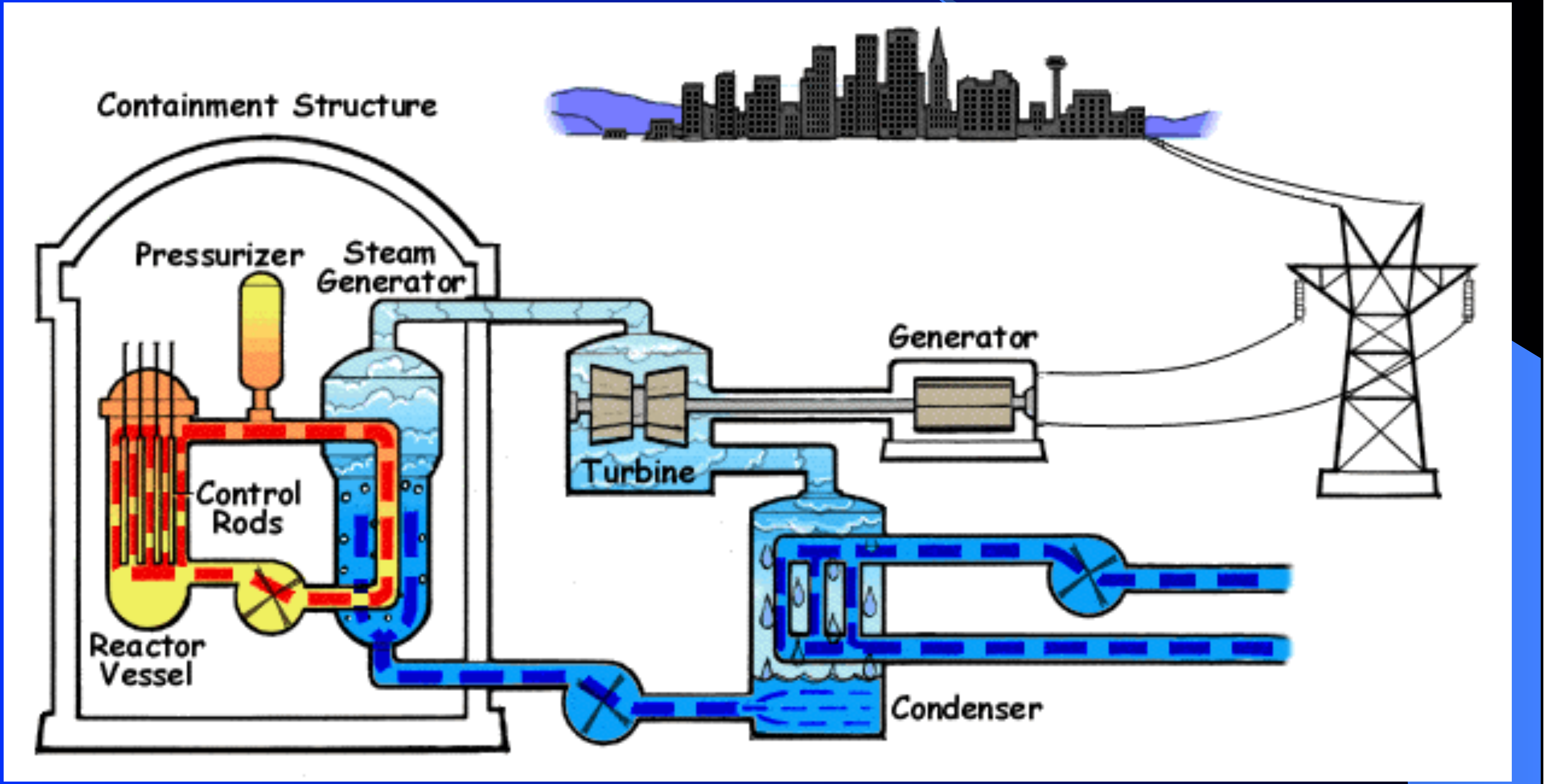
The amount of energy extracted from nuclear fuel is called its burnup, which is expressed in terms of the heat energy produced per initial unit of fuel weight. Burn up is commonly expressed as megawatt days thermal per metric ton of initial heavy metal.

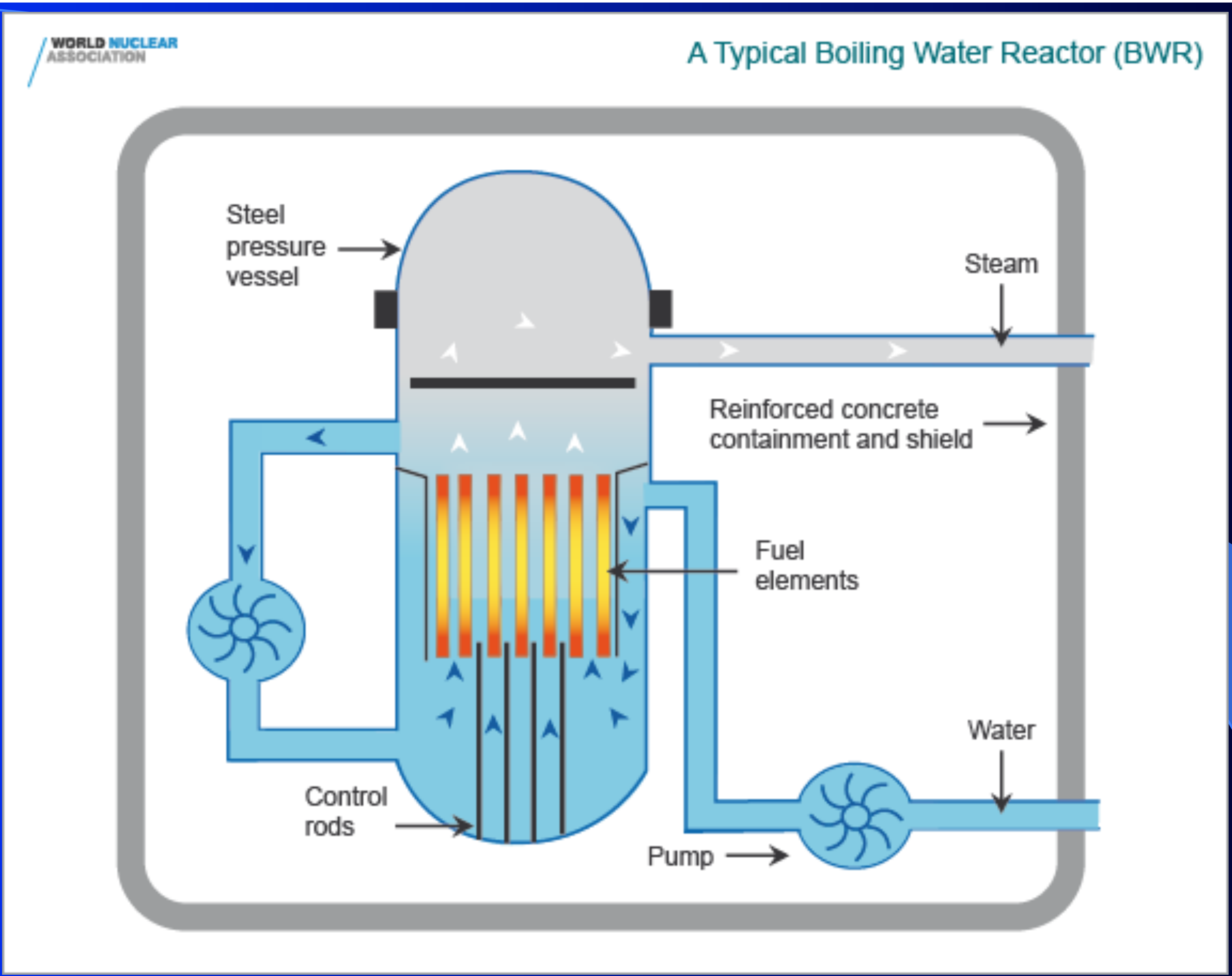


Pressurised Water Reactor (PWR)

This is the most common type, with over 230 in use for power generation and several hundred more employed for naval propulsion. The design of PWRs originated as a submarine power plant. PWRs use ordinary water as both coolant and moderator. The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine

Pressurised Water Reactor (PWR)

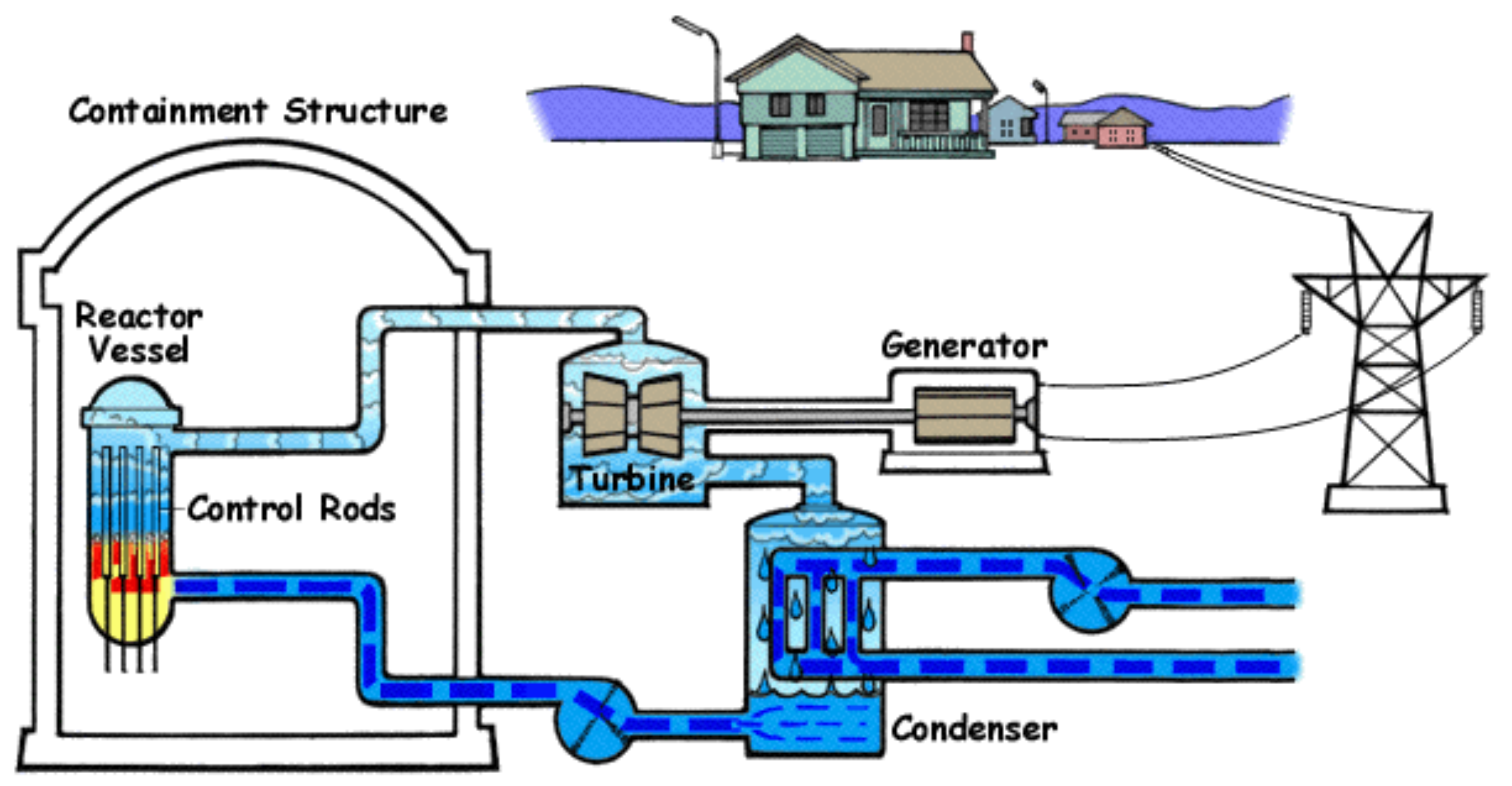


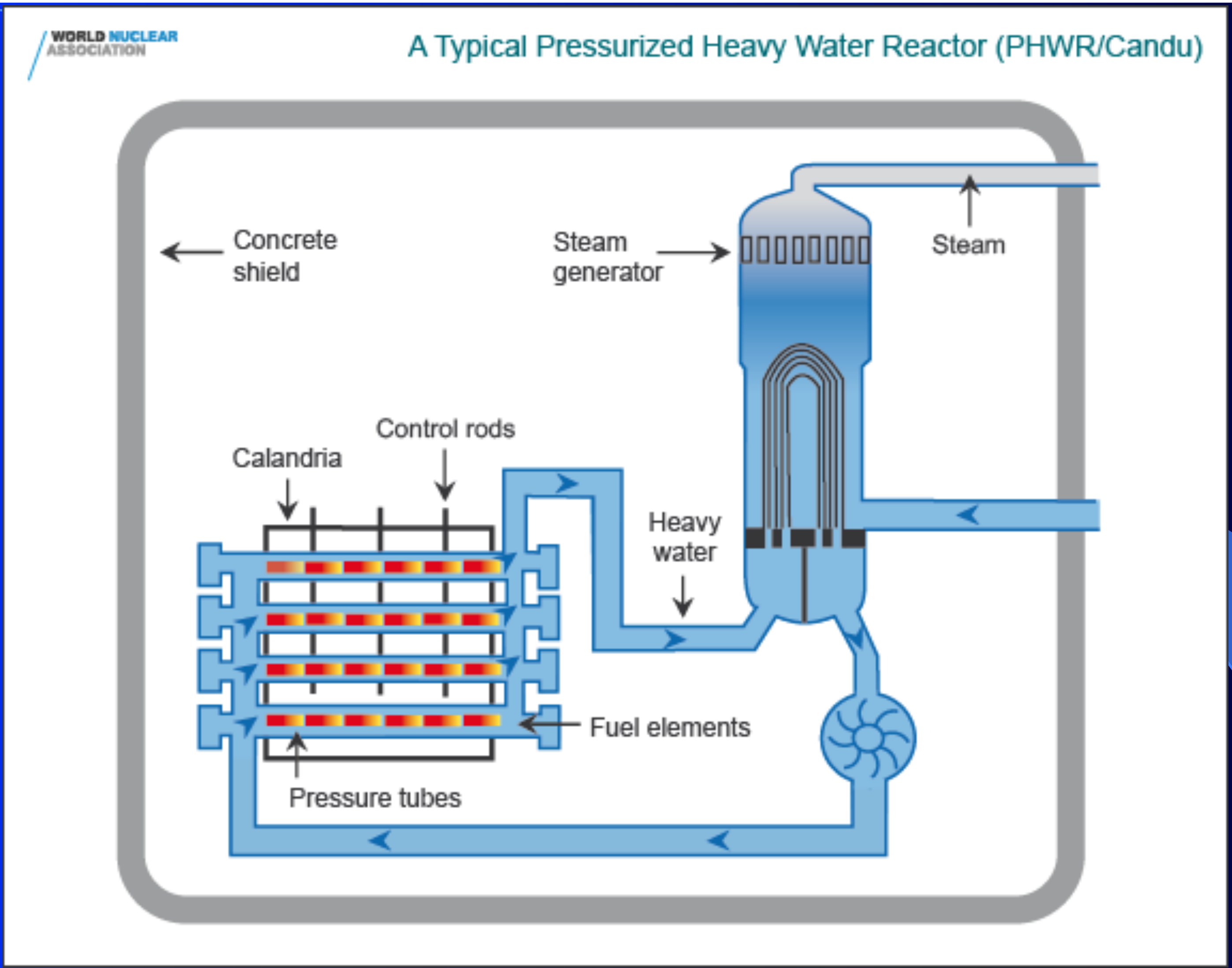


Boiling Water Reactor (BWR)

This design has many similarities to the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C. The reactor is designed to operate with 12-15% of the water in the top part of the core as steam, and hence with less moderating effect and thus efficiency there

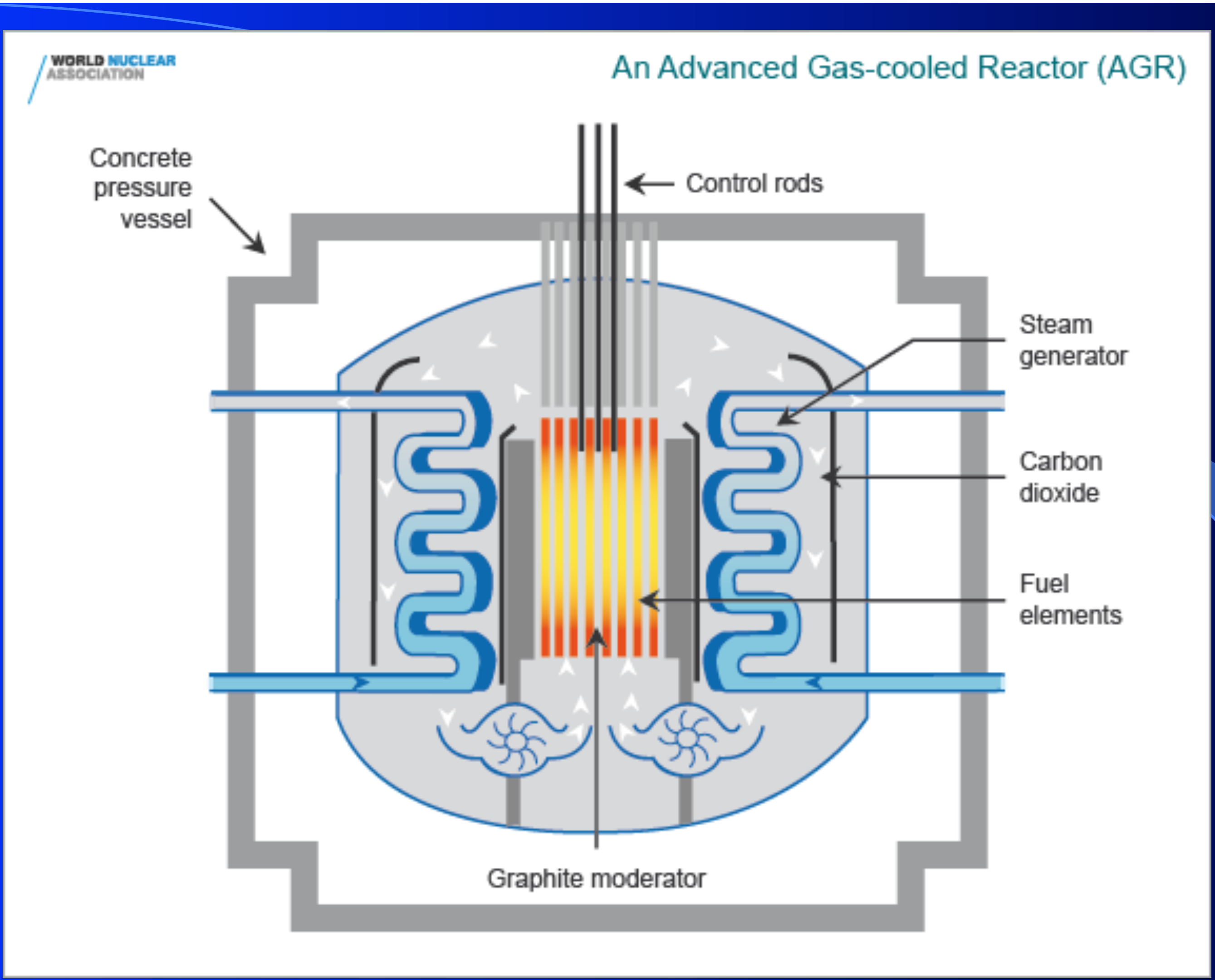
Boiling Water Reactor (BWR)





Pressurised Heavy Water Reactor (PHWR or CANDU)

PHWRs generally **use natural uranium (0.7% U-235) oxide as fuel,** hence needs a more efficient moderator, in this case heavy water (D2O).** The PHWR produces more energy per kilogram of mined uranium than other designs, but also produces a much larger amount of used fuel per unit output.

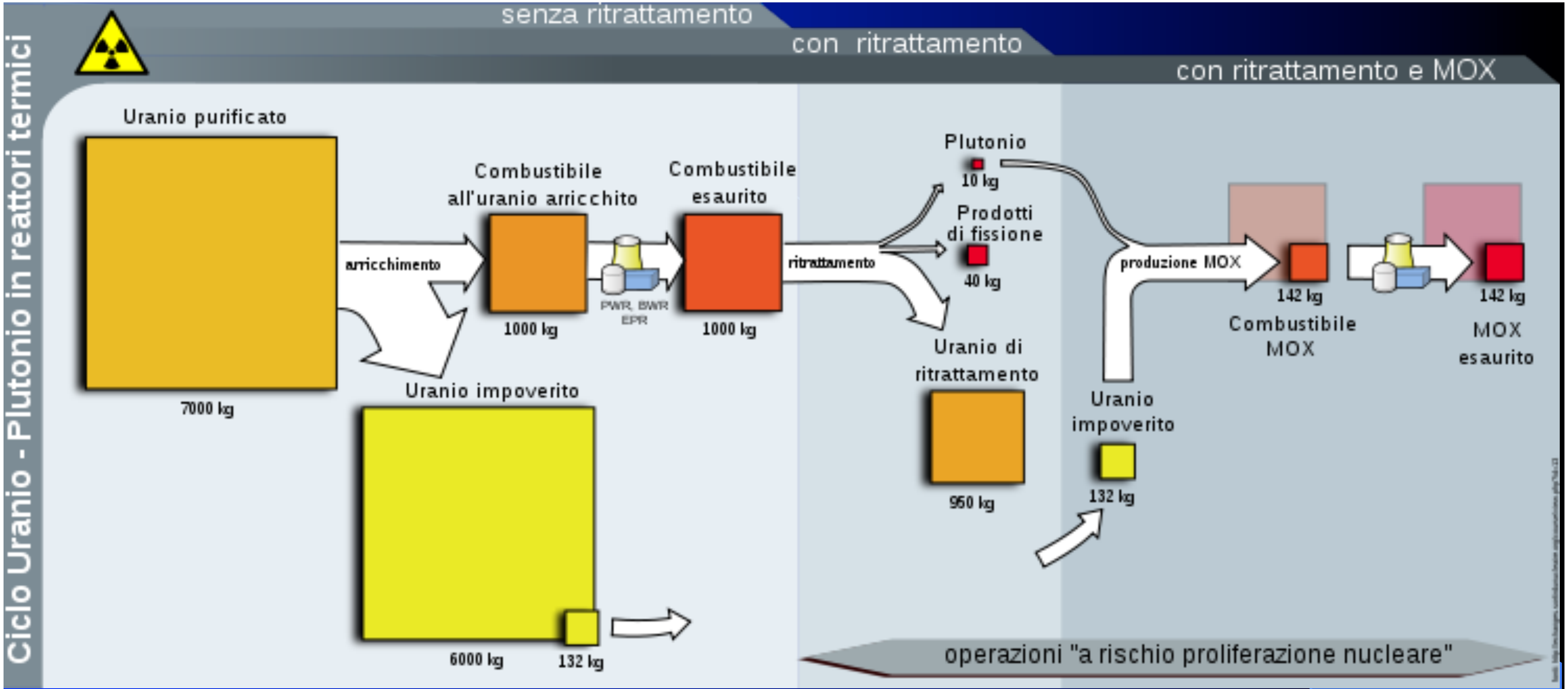


Advanced Gas-cooled Reactor (AGR)

These are the second generation of British gas-cooled reactors, using **graphite moderator** and **carbon dioxide** as primary coolant. The fuel is **uranium oxide pellets, enriched to 2.5-3.5%**, in stainless steel tubes. The carbon dioxide circulates through the core, reaching 650°C and then past steam generator tubes outside it, but still inside the concrete and steel pressure vessel (hence 'integral' design). Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen to the coolant.

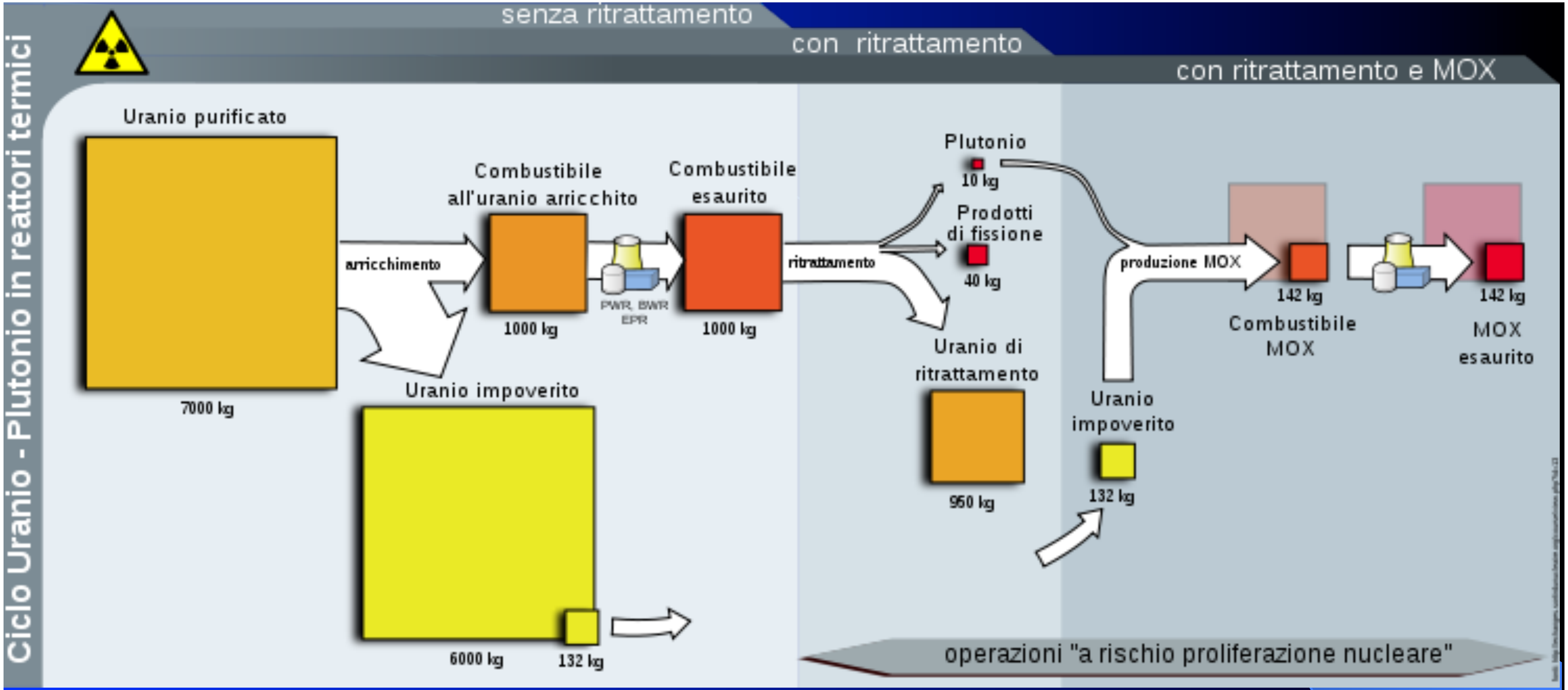
scorie radioattive:

- scarto di combustibile nucleare esausto derivante dalla fissione nucleare nel nocciolo reattore nucleare a fissione.
- il combustibile esausto è considerato scoria nucleare di **III categoria**, cioè scorie di alta radiotossicità e di grande persistenza nell'ambiente.
    - una quota di atomi "trasmutati" che hanno "catturato" uno o più neutroni senza "spezzarsi" e si sono dunque "appesantiti" (si tratta di elementi facenti parte del gruppo degli attinidi, e.g. ^{239}Pu, ^{240}Pu).
    - una parte di cosiddetti **prodotti di fissione** cioè di atomi che sono stati effettivamente "spezzati" dalla fissione e sono pertanto molto più "leggeri" dei nuclei di partenza (e.g. ^{137}Cs, ^{90}Sr)
- **scorie di I e II categoria sono** invece i prodotti contaminati o rifiuti radiologici da ambito nucleare, industriale e radioterapico; per esempio le tute antiradiazioni usate da chi lavora nelle centrali hanno una radioattività bassissima e sono classificate come scorie nucleari di I categoria.



Ciclo attuale del combustibile nucleare all'uranio per 1000 kg di combustibile in reattori a neutroni termici.

- A partire dall'uranio purificato, si ottiene **il combustibile arricchito (al 3.5% di ^{235}U)** ed una grande quantità di **uranio impoverito di scarto**.
- Dopo l'uso in reattori, si ottiene il "**combustibile esaurito" che è estremamente più pericoloso e radiotossico dell'uranio di partenza**. La maggior parte dei paesi dotati di impianti nucleari (per es. gli USA) considerano il combustibile esaurito come scorie nucleari da smaltire.
- **Il combustibile esaurito può essere riprocessato per separarne le componenti**, con particolare interesse per il **plutonio**, considerando come scorie solamente i prodotti di fissione; si ricava anche una gran quantità di uranio di ritrattamento che tuttavia non è adatto al riutilizzo in reattori nucleari in quanto contaminato da altri atomi pesanti.
- Il riprocessamento può essere effettuato a **scopo civile o militare**, in quest'ultimo caso a scopo di ottenere materiale per la **costruzione di armi atomiche**.



- A partire dagli anni ottanta, specialmente in Francia, è stato messo a punto un **combustibile costituito da plutonio ed uranio impoverito**, denominato **MOX** (mixed oxides, ossidi misti, a causa del fatto che è costituito da biossido di plutonio e biossido di uranio impoverito).
- Il MOX esaurito, rispetto al combustibile esaurito bruciato una sola volta, contiene un tenore ancora più elevato di ^{240}Pu ed isotopi superiori, rendendo più problematico e quindi più antieconomico un ulteriore ritrattatamento.