CH1002 Energy Management in Chemical Industries

Nuclear Power

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Introduction

- Generating power by harnessing the radioactivity of atoms
- Nuclear fission – U235. Chain reaction leads to generation of large amount of heat, boils water, generates steam which drives steam turbine, and produces electricity
- Many military and some civilian (such as some icebreaker) ships use nuclear marine propulsion
- Risks: due to spent nuclear fuel, high initial costs

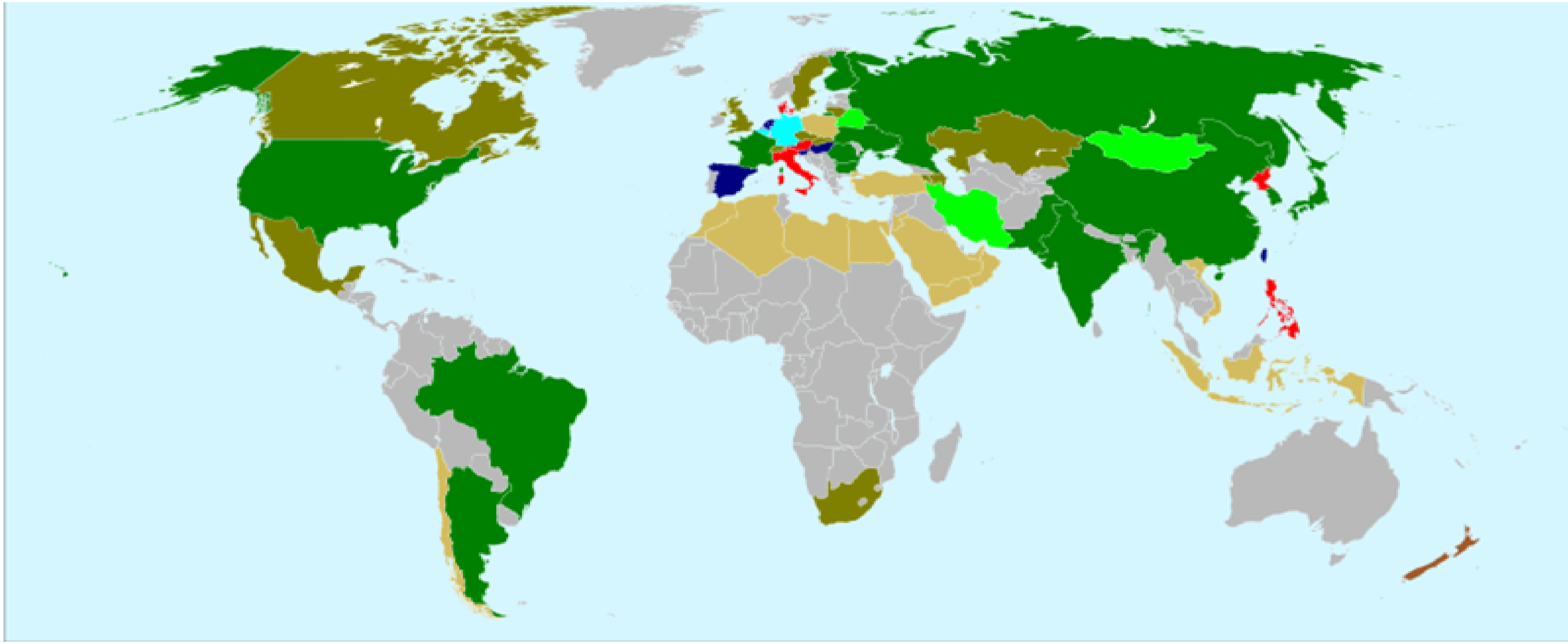
Status of Nuclear Power

- As of 2005, nuclear power provided 6.3% of the world's energy and 15% of the world's electricity, with the U.S., France, and Japan together accounting for 56.5% of nuclear generated electricity.

- In 2009, 13-14% of the world's electricity came from nuclear power.

- Different nations have different attitude towards nuclear power:
  - France generates most of their electricity by nuclear power
  - Germany planned to decommission all of their nuclear power stations
  - Jordan, Malaysia, Indonesia, UAE - decided to start new nuclear power installations

Nuclear Power by Country



- countries building their first reactors
- countries building new reactors
- countries planning/considering their first reactors
- countries planning/considering new reactors
- countries with reactors, but no plans for expansion or phase-out
- countries with reactors considering phase-out
- countries which formerly had commercial reactors, but which have all been phased out
- countries without commercial reactors
- countries that have declared themselves free of nuclear power and weapons

Source: http://en.wikipedia.org/wiki/Nuclear_power_by_country (28-May-2009)

Dependence of nations on nuclear energy in 2000

Country	Electric energy from nuclear energy (billion kWh)	Total electricity generation (billion kWh)	Nuclear share (% national total)
United States	753.9	3799.9	19.8%
France	394.4	513.9	76.7%
Japan	293.8	1014.7	29.0%
Germany	161.2	537.3	30.0%
Russia	122.5	835.6	14.7%
South Korea	103.5	273.2	37.9%
United Kingdom	81.7	355.8	23.0%
Ukraine	71.1	163.6	43.5%
Canada	68.7	576.2	11.9%
Spain	58.9	211.6	27.8%

Source: Table 6.3, EIA website, 2002.

Nuclear Power Plants in India

Current Installations (19 units): 4560 MW

Under construction (6 units) : 5020 MW

Target: 20 GW, by the year 2020

Atomic Power Stations in India

Active plants

Plants under construction

Souce: http://en.wikipedia.org/wiki/Template:India_nuke_plant_map (28-May-2009)

Current Installations in India

Power Station	**State**	**Units**	**Total Capacity (MW)**
Madras Atomic Power Station (MAPS)	Tamil Nadu	220 x 2	440
Kaiga Generating Station	Karnataka	220 x 3	660
Tarapur Atomic Power Station (TAPS)	Maharashtra	160 x 2 540 x 2	1400
Kakrapar Atomic Power Station (KAPS)	Gujarat	220 x 2	440
Rajasthan Atomic Power Station (RAPS)	Rajasthan	100 x 1 200 x 1 220 x 4	1180
Narora Atomic Power Station (NAPS)	Uttar Pradesh	220 x 2	440
		Total	**4560**

Source: http://www.npcil.nic.in; 26-July-2010

Plants Under Construction

Project	Capacity (MW)	Expected Commercial Operation
Kudankulam Atomic Power Project	1000 x 2	Unit 1 – Dec-2010 Unit 2 – Jun-2011
Rajasthan Atomic Power Project	700 x 2	Unit 7 – Jun-2016 Unit 8 – Dec-2016
Kaiga Atomic Power Project	220 x 1	Unit 4 – Aug-2010
Kakrapur Atomic Power Project	700 x 2	Unit 3 – Jun-2015 Unit 4 – Dec-2015

Source: http://www.npcil.nic.in; 26-July-2010

India’s Nuclear Reserves and Utilization

- The domestic reserve of 80,000 to 112,000 tons of uranium (approx 1% of global uranium reserves) is large enough to supply all of India's commercial and military reactors as well as supply all the needs of India's nuclear weapons arsenal.

- Currently, India's nuclear power reactors consume, at most, 478 metric tonnes of uranium per year. Even if India were quadruple its nuclear power output (and reactor base) to 20GW by 2020, nuclear power generation would only consume 2000 metric tonnes of uranium per annum.

- Based on India's known commercially viable reserves of 80,000 to 112,000 tons of uranium, this represents a 40 to 50 years uranium supply for India's nuclear power reactors (note with reprocessing and breeder reactor technology, this supply could be stretched out many times over).

Nuclear Energy

- Nuclear energy is derived from the binding force (the "strong" force) that holds the nucleons of the atomic nucleus together. The binding force per nucleon is greatest for elements in the middle of the periodic table and is smallest for the lighter and heavier elements.

- When lighter nuclei *fuse* together, energy is released; Also, when heavier nuclei undergo *fission,* energy is released.

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{144}\mathrm{Ba} + {}^{89}\mathrm{Kr} + 3\mathrm{n} + 177\mathrm{MeV}$$

n stands for a neutron; 1 atom of ^{235}U produces 177 MeV

- The fission of 1 kg of ^{235}U produces 7.3 x 10^{13} J. In comparison, the combustion of 1 kg of carbon produces 3.3 x 10^{7} J, which is about 2 million times less energy per unit weight than a fission reaction.

Fission of ^{235}U to the formation of ^{239}Pu

- At the same time that ^{235}U splits into fission products with the release of 2–3 neutrons, a part of the neutrons can be absorbed by the more abundant 238U in the fuel, converting it in a series of reactions to an isotope of plutonium, ^{239}Pu:

$$^{238}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}\mathrm{U} + \gamma \rightarrow {}^{239}\mathrm{Np} + \beta \rightarrow {}^{239}\mathrm{Pu} + \beta$$

Fuel Requirement

- Murray [2001, page 140] pointed out that a pressurized water reactor generates 1 MWt·day of thermal energy from the consumption of about 1.3 g of uranium-235.

- If we assume 33% efficiency, a reactor that requires an annual thermal power input of 300 MWt will generate an *annual electrical power output of 100 MWe* while consuming approximately *142 kg of uranium-235*.

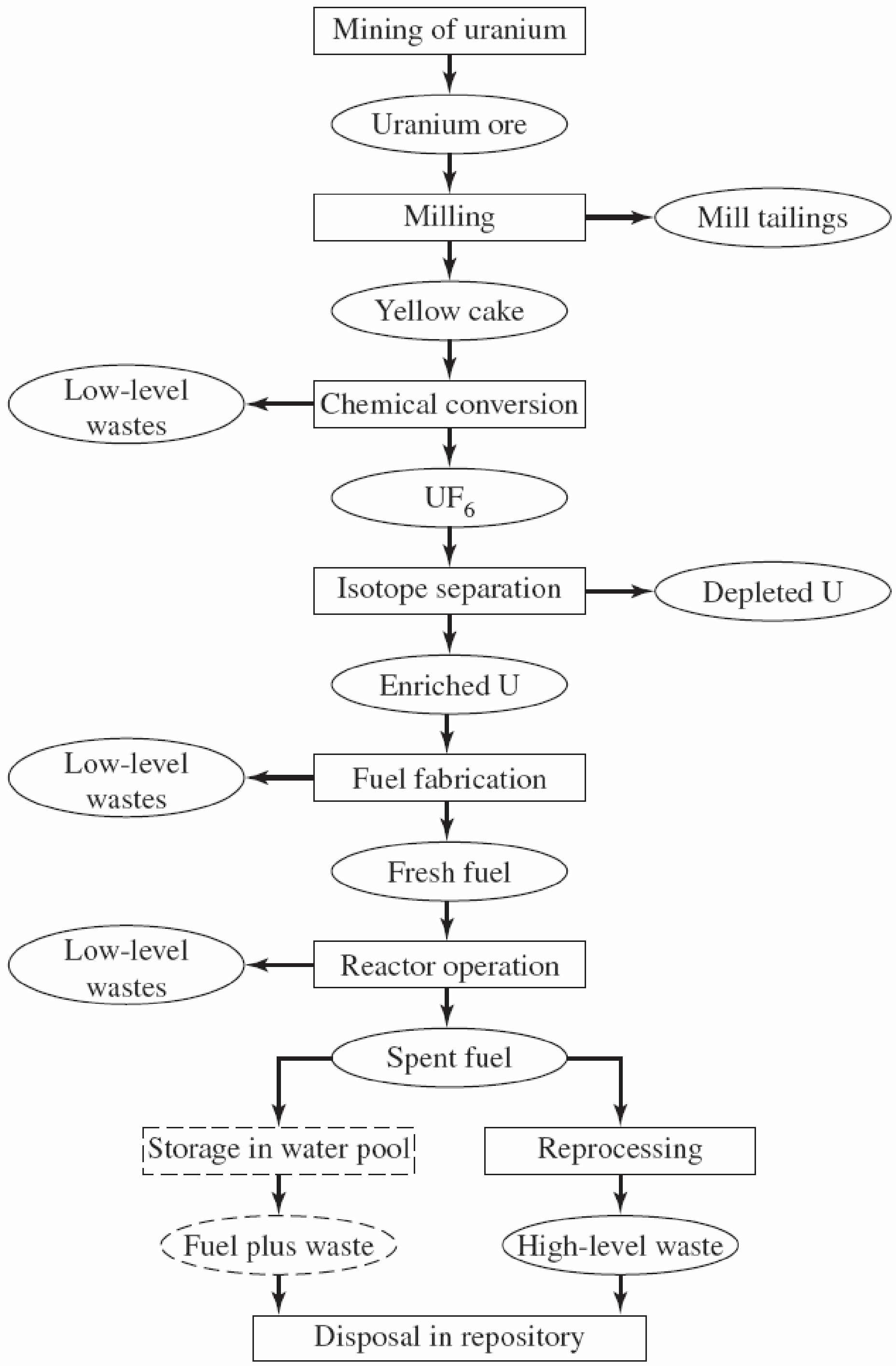
Uranium Availability

- The most abundant fuel for nuclear fission is uranium. Uranium exists in the crust of the earth as the mineral uraninite.
- Uraninite is commonly called pitchblende and is a uranium oxide (U_3O_8). It is found in veins in granites and other igneous rocks. It is possible to find uranium in sedimentary rocks.

Nuclear Fuel Cycle

The nuclear fuel cycle starts from mining uranium (or thorium) ore, through extraction of the useful uranium concentrate, gasification to UF_6, enrichment of ^{235}U, conversion to metallic uranium or oxide of uranium, fuel rod fabrication, loading of a reactor, retrieval of spent fuel, reprocessing of spent fuel, and finally fuel waste disposal.

Nuclear Fuel Cycle



Source: Fay and Golomb, Energy and Environment, Oxford University Press, New York, 2002

Nuclear Reactor

- The basic ingredients of a nuclear reactor are *fuel rods,* a *moderator, control rods,* and a *coolant.*
- In a nuclear reactor of a power plant, the splitting of the nucleus and sustaining of the ensuing chain reaction has to proceed in a controlled fashion.
- The *fuel rods* contain the fissile isotopes ^{235}U and/or ^{239}Pu.
- Natural uranium contains about 99.3% ^{238}U and 0.7% ^{235}U. The concentration of the fissile isotope ^{235}U in natural uranium is not enough to sustain a chain reaction in most power plant reactors; therefore, this isotope needs to be “enriched” to 3–4%
- The fuel rods contain metallic uranium, solid uranium dioxide (UO_2), or a mix of uranium dioxide and plutonium oxide, called MOX, fabricated into ceramic pellets. The pellets are loaded into zircalloy or stainless steel tubes, about 1-cm diameter and up to 4 m long.

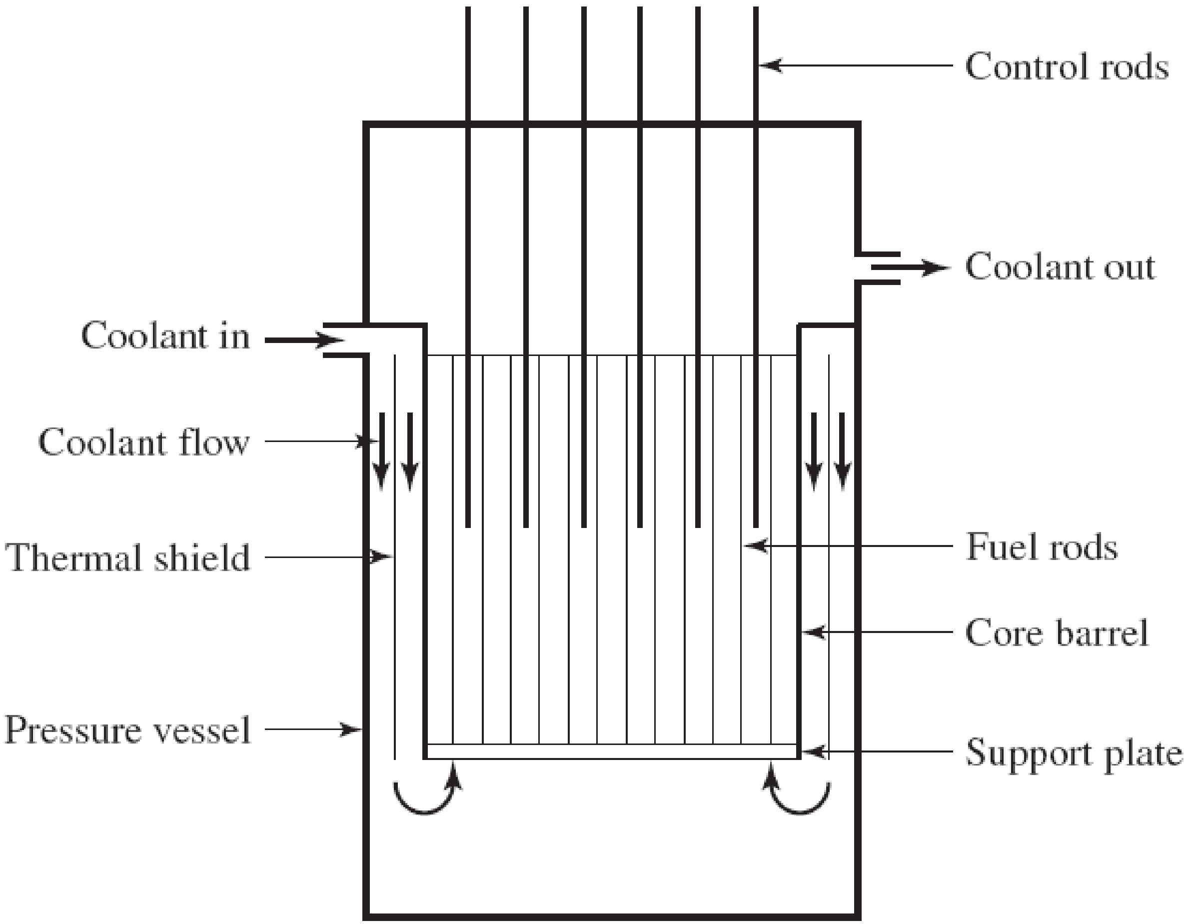
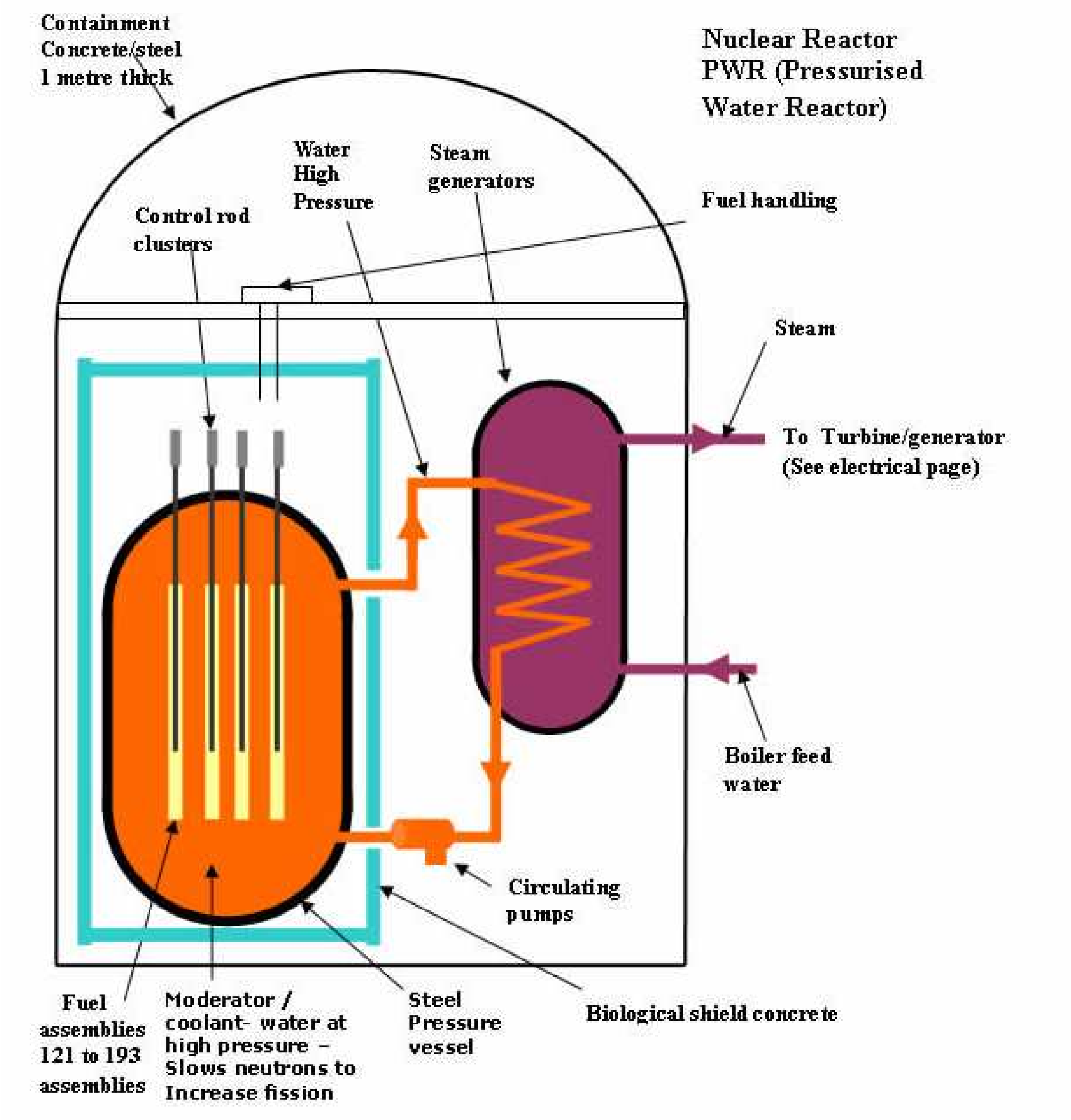
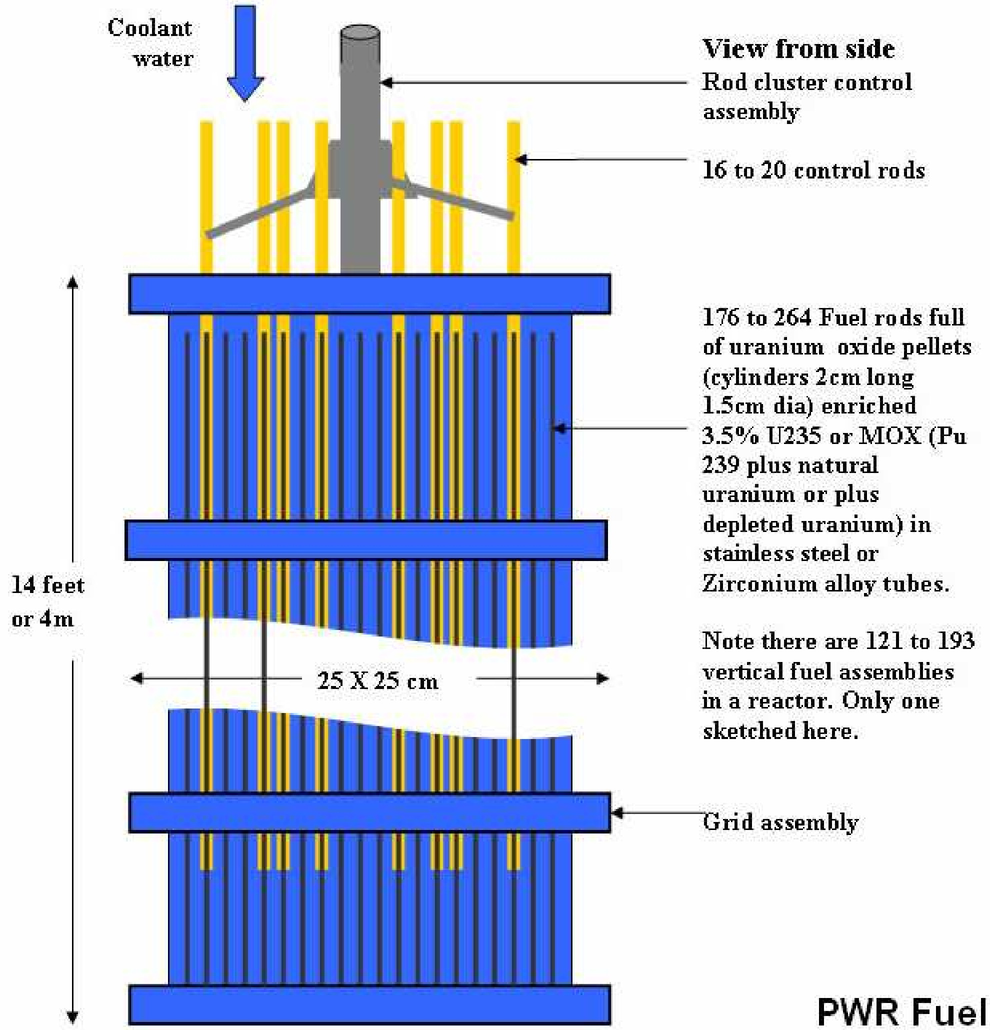


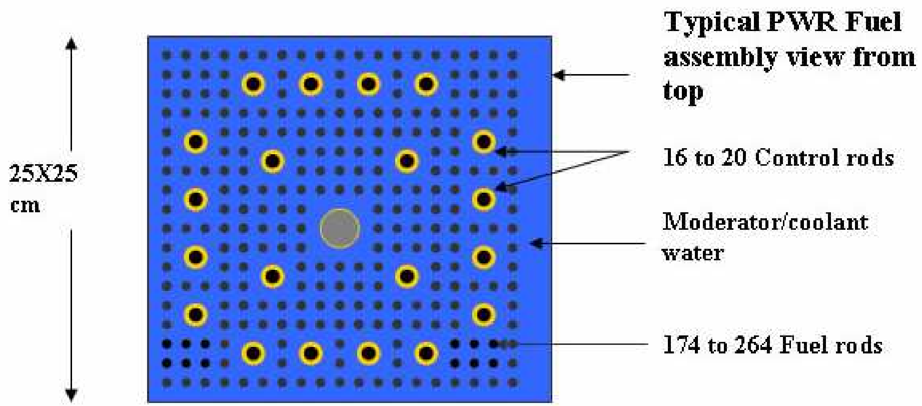
Figure 6.1 Schematic of nuclear reactor with water as coolant/moderator.

Source: Fay and Golomb, Environment and Energy, Oxford University Press, New York, 2002.

Pressurized Water Reactor







PWR Fuel assemblies

Nuclear Reactor (contd.)

- ***Moderators:***
  - *Moderators* are used to slow the energetic neutrons that evolve from the fission reaction, yielding low-energy neutrons, also called thermal neutrons. This increases the probability for the neutrons to be absorbed in another fissile nucleus, so that the chain reaction can be propagated.
  - Moderators contain atoms or molecules whose nuclei have high neutron scattering and low neutron absorption characteristics.
  - Typical moderators are light water (H_2O), heavy water (D_2O), graphite (C), and beryllium (Be). The light or heavy water moderators circulate around the fuel rods. Graphite or beryllium moderators constitute a block into which fuel rods are inserted.

Nuclear Reactor (contd.)

- ***Control rods:***
  - Control rods contain elements whose nuclei have a high probability of absorbing thermal neutrons, so that they are not available for further splitting of fissile nuclei.
  - In the presence of control rods, the chain reaction is controlled or stopped altogether.
  - Typical control rods are made of boron (B) or cadmium (Cd).
  - The position of the control rods determines the power output of the reactor.

Nuclear Reactor (contd.)

- Once the remaining fuel in the rods cannot sustain the rated capacity of the plant, even with complete withdrawal of the control rods, the fuel rods need to be replaced. This occurs every 2–3 years.

- Heat must be constantly removed from the reactor.

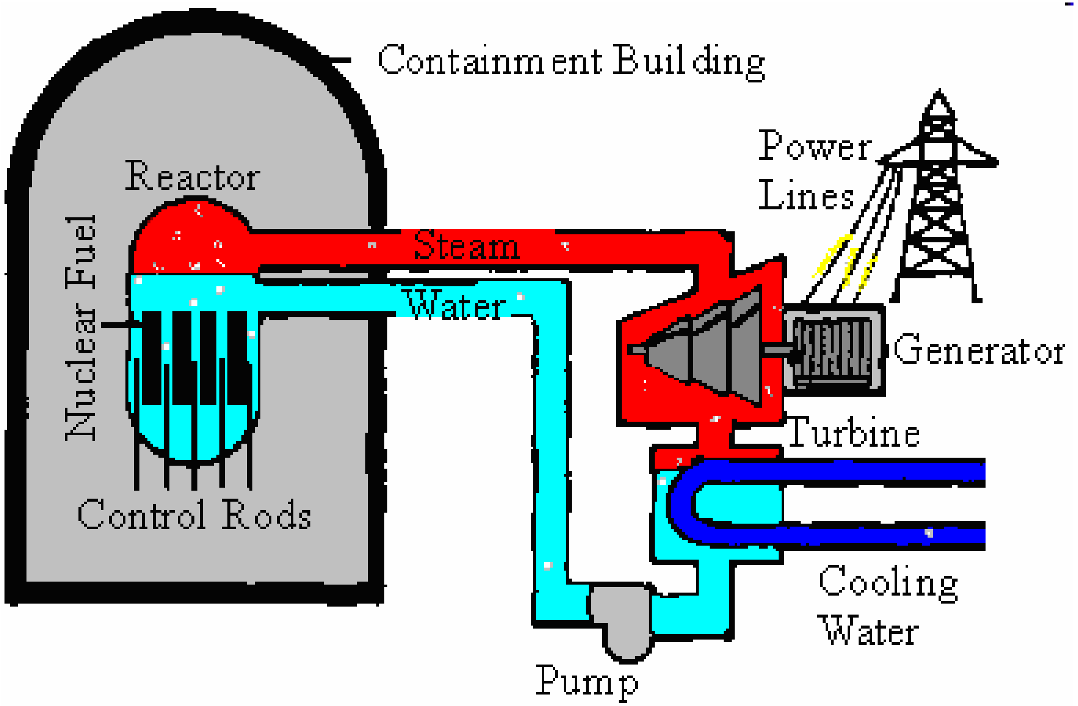
- Heat is removed by a *coolant,* which can be boiling water, pressurized water, a molten metal (e.g., liquid sodium), or a gas (helium or CO_2).

- The heat removed by the coolant, in the form of steam or pressurized hot water, is used in conventional thermodynamic cycles to produce mechanical and electrical energy.

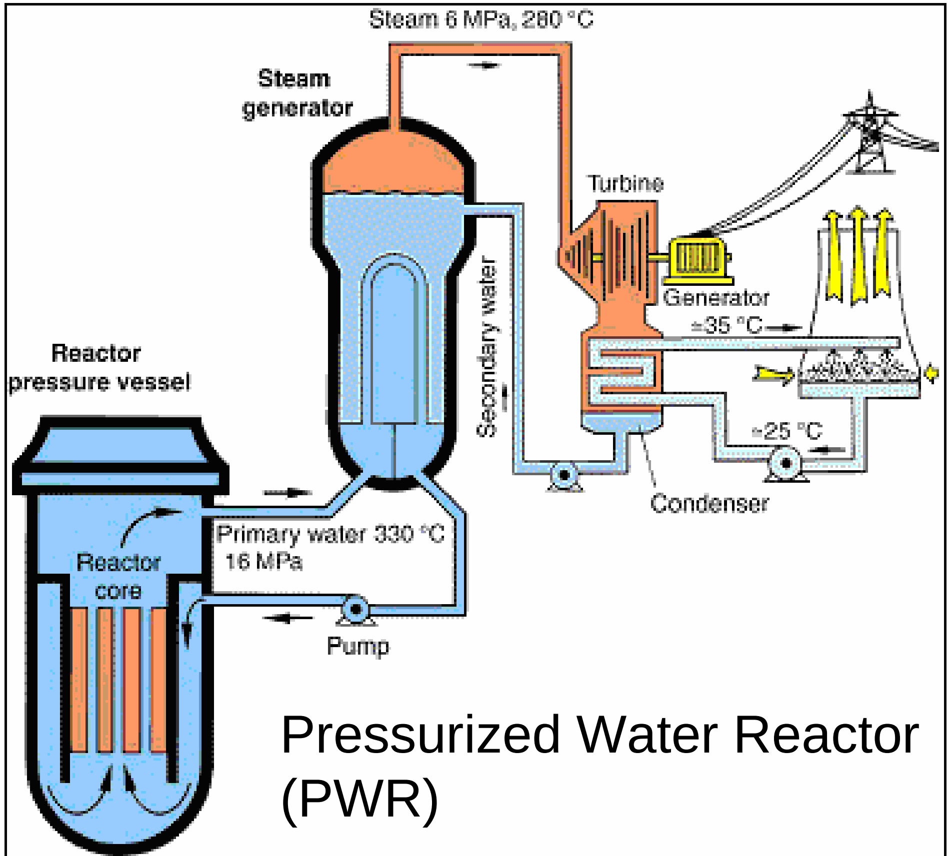
Types of Nuclear Reactors

Reactor Type	Coolant	Moderator	Fuel	Comment
Pressurised water reactors (PWR, VVER)	Light water	Light water	Enriched uranium	Steam gener-ated in secondar y loop
Boiling water reactors (BWR)	Light water	Light water	Enriched uranium	Steam from boiling water fed to turbine
Pressurised heavy water reactor (PHWR)	Heavy water	Heavy water	Natural uranium	
Gas-cooled reactors (Magnox, AGR, UNGG)	CO_2	Graphite	Natural or enriched uranium	
Light water graphite reactors (RBMK)	Press-urised boiling water	Graphite	Enriched uranium	Soviet design

Most of the current power plants use pressurized water type (PWR)

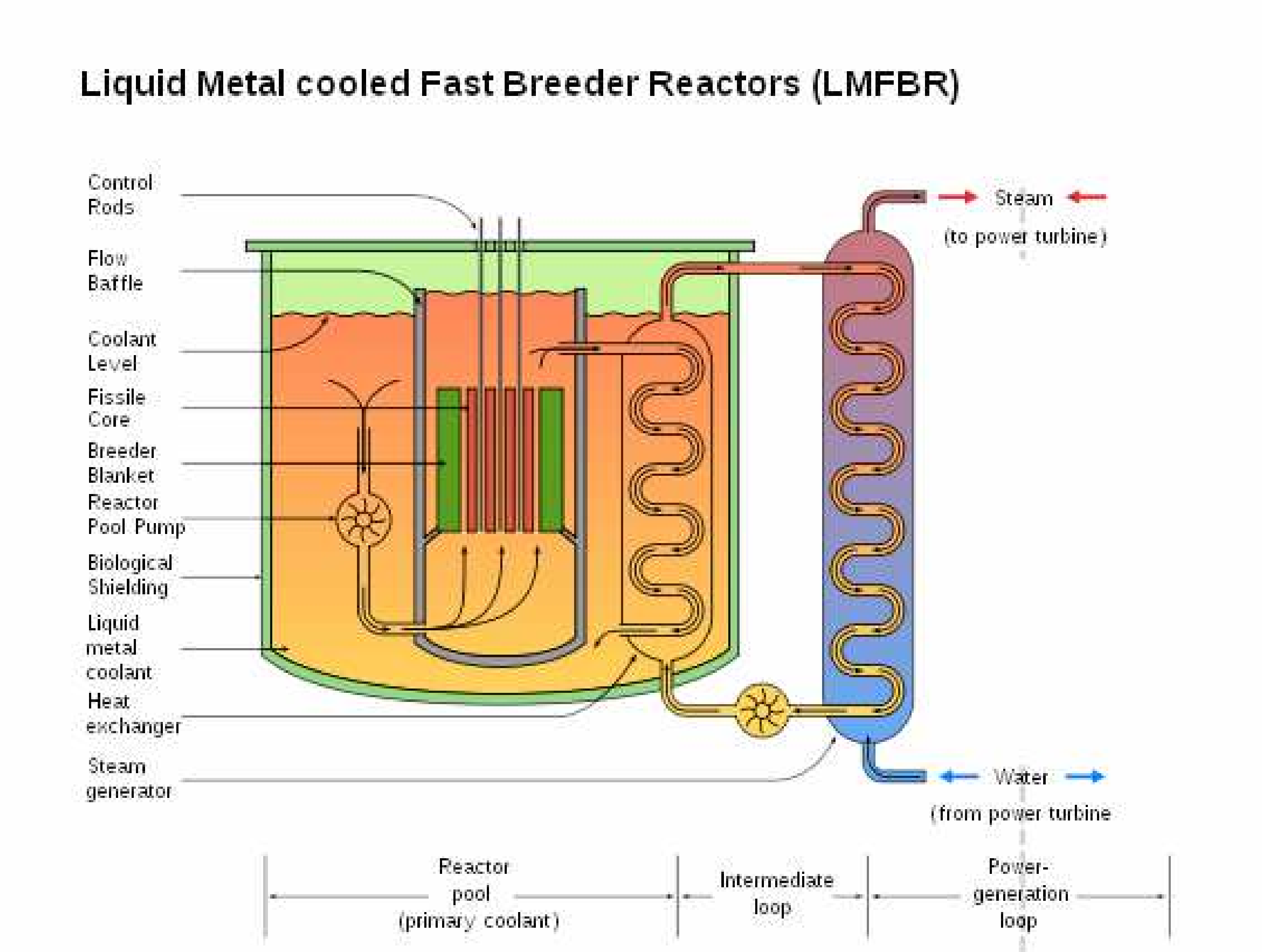


Boiling Water Reactor (BWR)



Pressurized Water Reactor (PWR)

Fast Breeder Reactor (FBR)



FBR

- The plutonium-239 breeder reactor is commonly called a fast breeder reactor, and the cooling and heat transfer is done by a liquid metal. The metals which can accomplish this are sodium and lithium, with sodium being the most abundant and most commonly used.

- The construction of the fast breeder requires a higher enrichment of U-235 than a light-water reactor, typically 15 to 30%. The reactor fuel is surrounded by a "blanket" of non-fissionable U-238.

- No moderator is used in the breeder reactor since fast neutrons are more efficient in transmuting U-238 to Pu-239. At this concentration of U-235, the cross-section for fission with fast neutrons is sufficient to sustain the chain-reaction.

- Using water as coolant would slow down the neutrons, but the use of liquid sodium avoids that moderation and provides a very efficient heat transfer medium.

FBR (contd.)

- Breeder reactors have been primarily used to produce weapons-grade plutonium.
- They use natural uranium and a coolant/moderator that usually is liquid sodium.
- Most of the breeder reactors have been phased out since sufficient plutonium for weapons production has been stockpiled, and there is no immediate scarcity of natural uranium.

Major Accidents and Issues

- **Three Mile Island** (1979, USA): Loss of coolant and partial core meltdown
- **Chernobyl** (1986, former USSR, Ukraine): Steam explosion and meltdown with 4,056 deaths necessitating the evacuation of 300,000 people from Kiev and dispersing radioactive material across Europe
- ***Persistent Problem:*** The issue of the disposal of the high-level radioactive waste that keeps accumulating at the plants has not been resolved in the United States and worldwide.