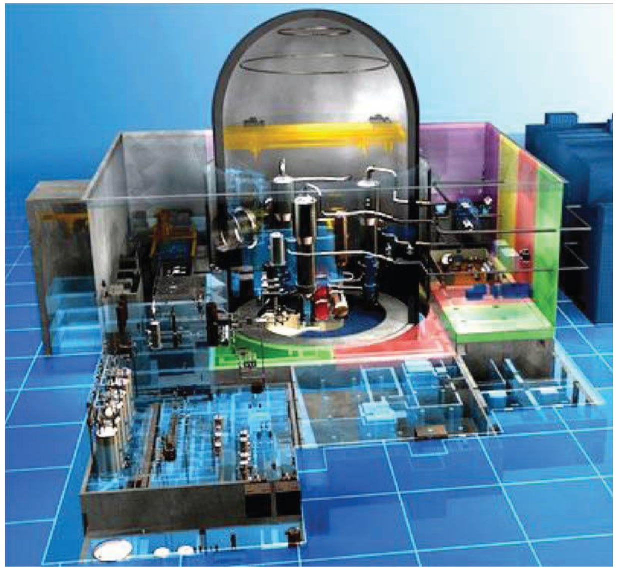
INTRODUCTION TO NUCLEAR REACTOR SYSTEM



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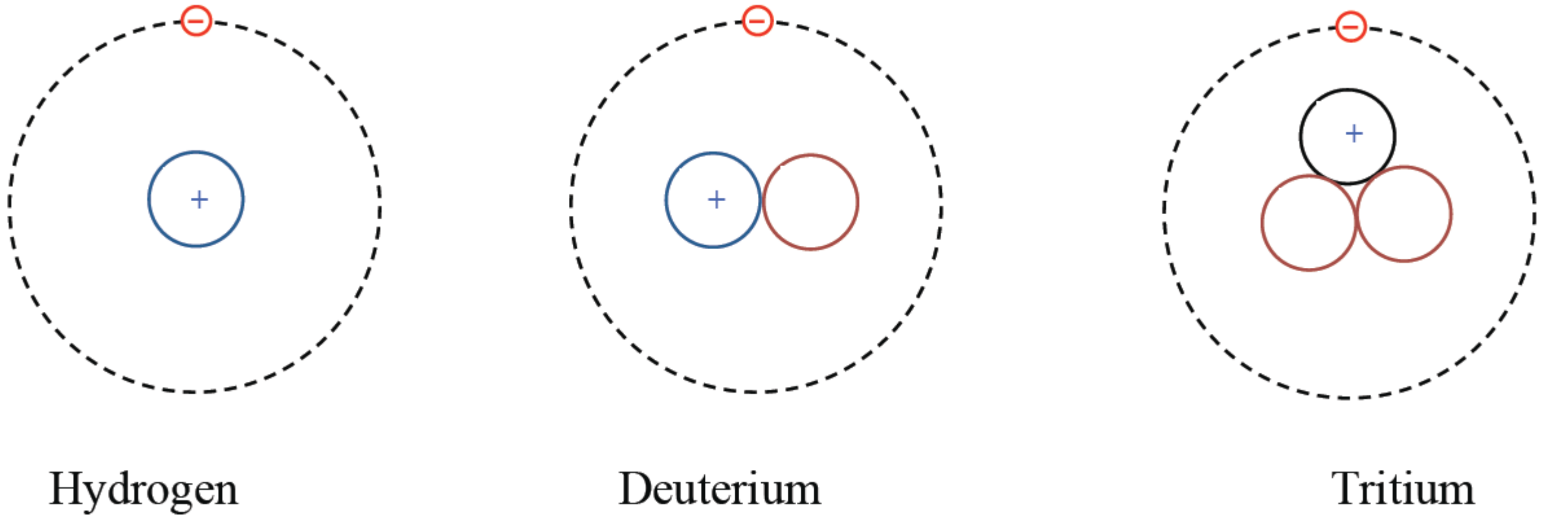
Objectives of topic

- Students able to explain the basic concept of a nucleus
- Students able to calculate the binding energy of a nucleus
- Students able to explain the neutron and nuclear reactors classification

Nucleus

- Nucleus is **positive**, due to the presence of positively charged **protons.**
- Few elements have same atomic number ‘Z’ but possess different mass number are called ***Isotopes***,
- **Deuterium** and **Tritium** being the isotopes of **Hydrogen**



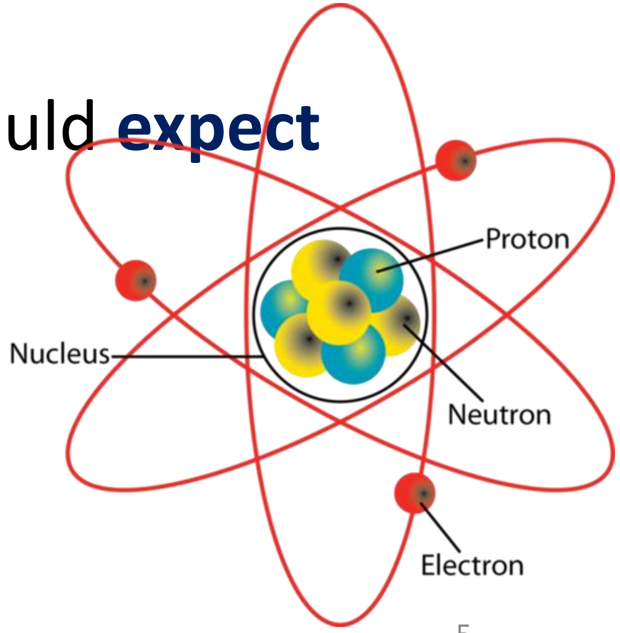
Nucleus cont.

- The difference between the **atomic mass** (A) and the **atomic number** (Z) is the **neutron number** (N).
- The **size** of a **nucleus** is much **lesser** than the size of **an atom**.
- Nucleus is **denser** than the **atom**, due to its **smaller volume** and **larger mass of protons**.
- The **radius** of a **nucleus** is related to the **number of nucleons** (A) as follows:

$$R(cm) = 1.25 \times 10^{-13} \cdot A^{1/3}$$

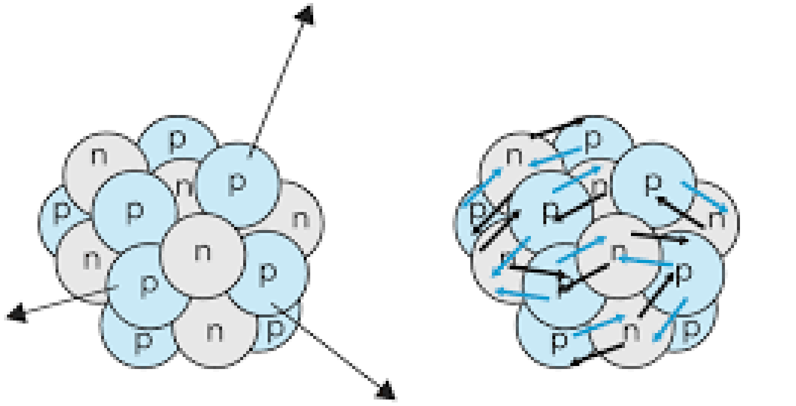
Binding Energy of a Nucleus (BE)

- As the **nucleus** contains **protons** (all of which are **positively charged**) and **neutrons** (**no charge**), one would expect **electrostatic repulsion** between **protons** to be **high**.
- **Electrostatic repulsion** between two charged particles **varies inversely** with the **square** of distance between **them**.
- Hence, as **two protons** come close to each other, one would **expect electrostatic repulsion** to make them **move apart**.



Binding Energy of a Nucleus (BE)

- However, the **existence of nucleus testifies** the fact that there exists a short-range **attractive force stronger** than the **electrostatic repulsion**.
- This short-range force is the ***nuclear force*** and is responsible for **binding *nucleons*** into a compact nucleus.
- A potential energy of binding (called **binding energy**) is associated with this **force**



Elastic repulsion of protons strains the nucleus

But the (residual) strong nuclear force holds the nucleus together

Binding Energy of a Nucleus (BE)

$$m_{CP} = Z(m_H) + N(m_n)$$

$\boldsymbol{m_n}$ Mass of a neutron
$\boldsymbol{m_H}$ Sum of mass of a proton and an electron
$\boldsymbol{m_{CP}}$ total mass of all constituent particles

The **difference** between the **total mass** of all constituent particles and that of the **atom** is the **mass defect** ($\boldsymbol{m_d}$)

$$m_d = Z(m_H) + N(m_n) - M = Z(1.007825) + N(1.008665) - M$$

$$\boldsymbol{BE = m_d c^2}$$

$\boldsymbol{M}$ Mass of the atom
$\boldsymbol{BE}$ Binding Energy
$\boldsymbol{c}$ Velocity of light in vacuum

$$Average\ binding\ energy = BE/A$$

Exercise 1

Determine the binding energy of the nucleus in $^{235}_{92}U$. The mass of ^{235}U atom is 235.0439231 amu

Given:

$$Z = 92; \quad A = 235; \quad N = A - Z = 143$$

$$M = 235.0439231\ amu$$

Exercise 2

Determine the average binding energy of the nucleus in $^{239}_{94}Pu$. The mass of ^{239}Pu atom is 239.052163 amu

Given:

$$Z = 94; \quad A = 239; \quad N = A - Z = 145$$

$$M = 239.052163\ amu$$

Neutron Classification

Depending on the **kinetic energy** of a neutron,
Classified two categories:

Thermal neutrons

Neutrons with kinetic energies of about 0.025 eV are called thermal neutron,

Fast neutrons

Neutrons with kinetic energies around 1 MeV

$$E = \frac{mv^2}{2}$$

Neutron Classification

At **20 °C**, the speeds of **thermal** and **fast** neutrons are **2.19 km/s** and **14000 km/s** respectively.

Quiz

How you get the speed of thermal and fast neutrons are **2.19 km/s** and **14000 km/s** respectively.

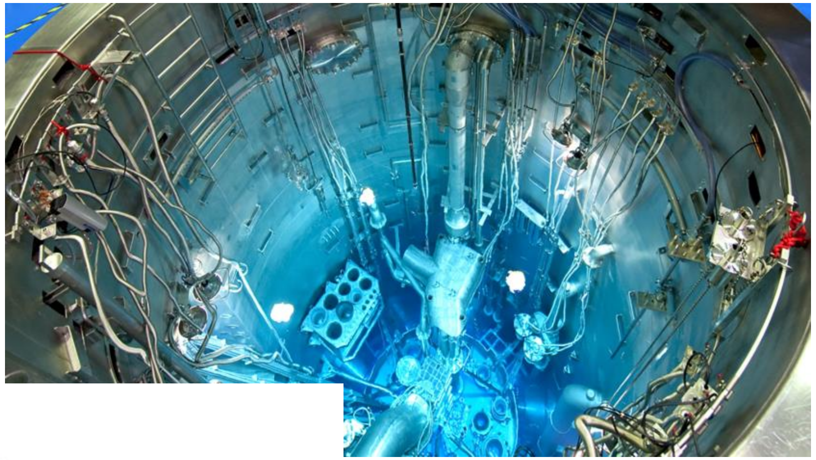
Given:

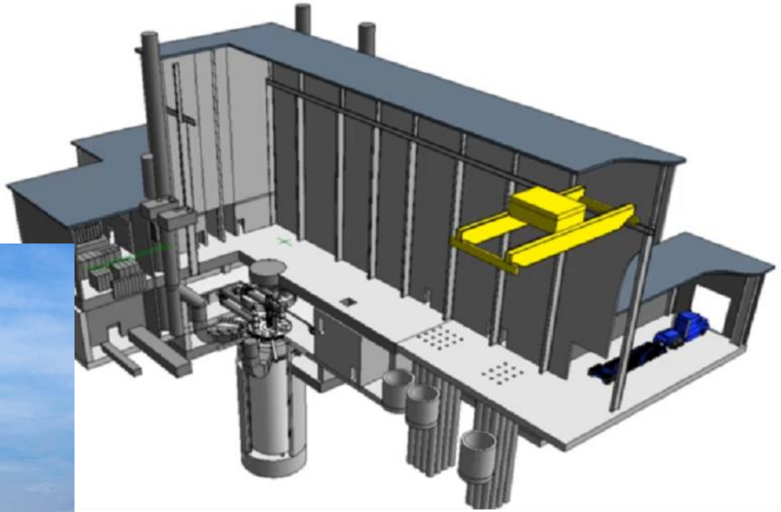
$$1\ ev = 1.60218 \times 10^{-19} J$$
$$m_n = 1.67493 \times 10^{-27} kg$$

Classification of Reactors

Nuclear reactors can be classified as

- Research reactor
- Test reactor
- Power reactor





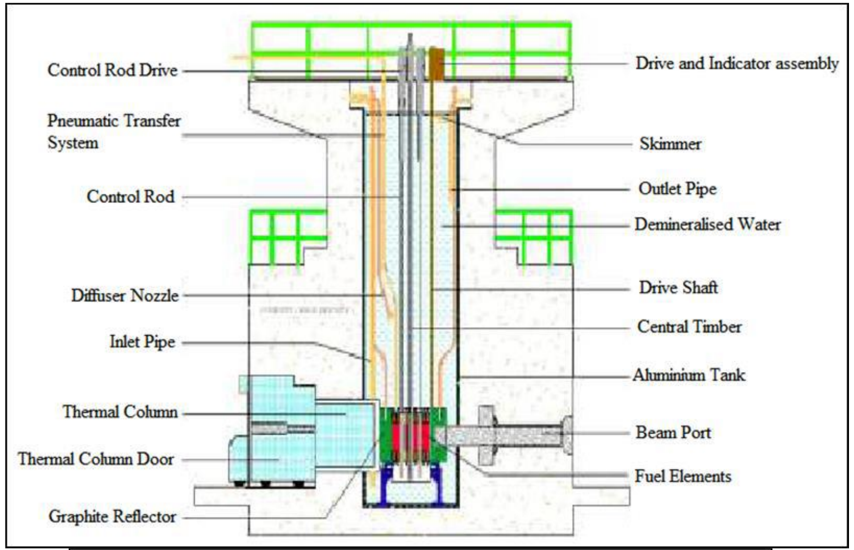
Research Reactors

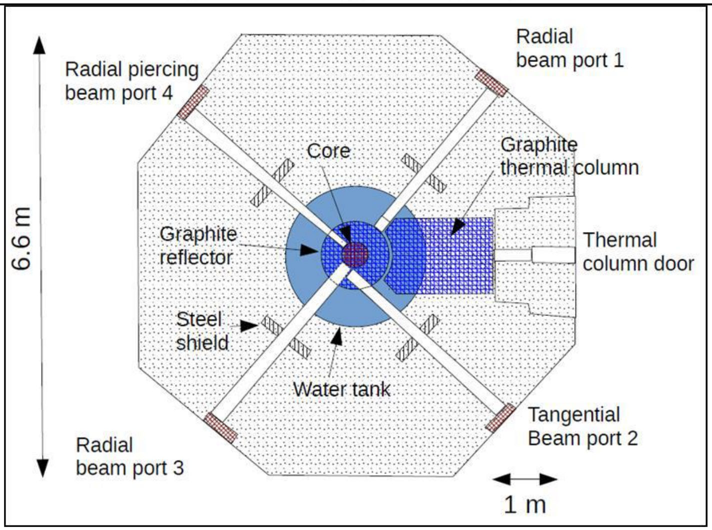
These were built for carrying out **basic** and **applied research** in various fields of **nuclear engineering** and its applications such as

- Neutron irradiation test for material testing.
- Development of materials for structures and other components.
- Educational and training of personnel for human resource development.
- Research in fission physics, solid state physics and radiation chemistry
- Radioisotopes production for medical and industrial use.
- Material studies.
- Non-destructive examination.
- Neutron activation analysis.

Our Research Reactor

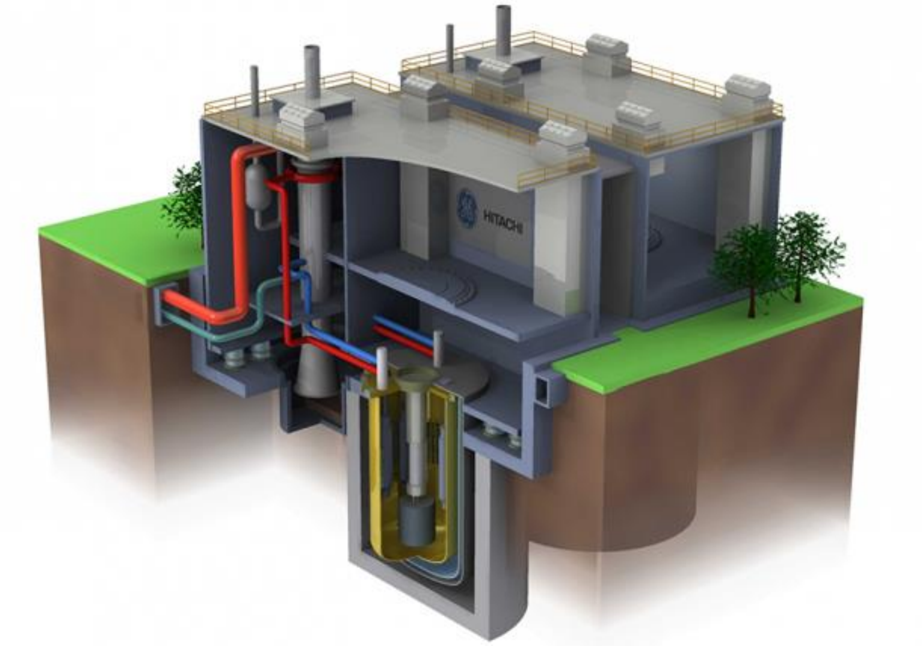
Name	**PUSPATI TRIGA MARK II Reactor (RTP)**
Purpose	Research in nuclear physics, radiation chemistry, biology, isotope production, shielding studies and training.
Type	Pool type reactor
First criticality	28th June 1982
Max. thermal power	1MW (steady state and square wave modes)
Average power density	23.36 W cm^{-3}
Max. thermal neutron flux	1.77×10^{13} $cm^{-2}s^{-1}$ (14th core configuration at 0.75 MW)
Shape and size of active core	Cylindrical, 21.26 in (54 cm dia.) x 15 in (38.1 cm height)
Coolant	Demineralized light water
Core cooling	Natural convection
Heat rejection	Two-loop cooling system
Moderator	Demineralized light water
Control rod	Boron carbide B_4C
Reflector	Graphite
Shape of fuel element	Cylindrical rod type
Fuel pellet	Uranium Zirconium Hydride (U-$ZrH_{1.6}$)
Fuel clad	Stainless steel 304
Enrichment of U^{235}	19.9%
Fuel element wt. %	8.5%, 12% and 20%





Test Reactor

- **Test reactors** are very **different** in **appearance** and **design** from **research reactor**, **nuclear power** reactors.
- This reactor has **served** as test reactor for **development** of various **technologies** for **nuclear reactor**.
- **Tests carried** out in this reactor have provided **valuable information** for the **design under the construction.**



GE Hitachi Nuclear Energy is working with Idaho National Laboratory on the Versatile Test Reactor concept design that is based off of its PRISM reactor

Power Reactors

Reactors used for **power generation** are called power reactors.

These can be further **classified** as follows:

- Based on the coolant
- Based on the operating pressure
- Based on the neutron energies
- Based on the moderator
- Based on the capability (fuel)

Power Reactors

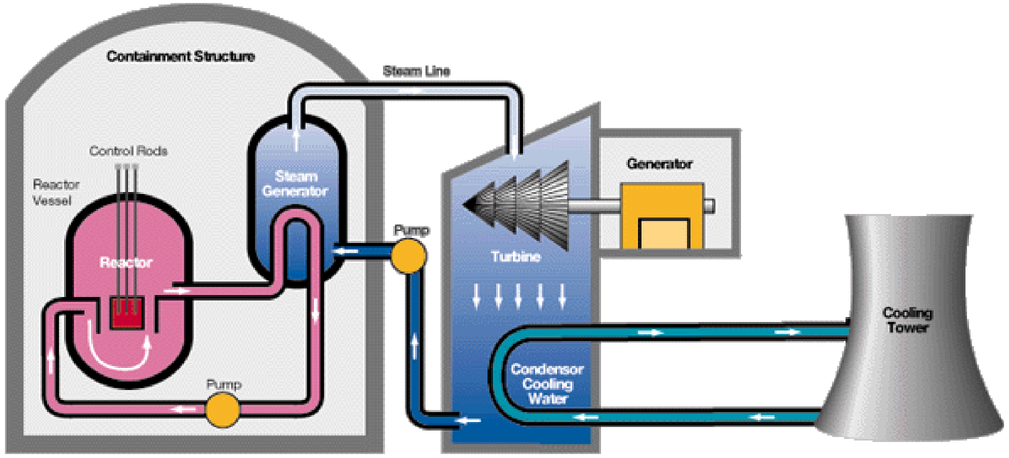
Based on the coolant:

- Light Water Reactor (light water as coolant).
- Heavy Water Reactor (heavy water as coolant).
- Gas-Cooled Reactor (CO2/He as coolant).
- Liquid Metal Cooled Reactor (liquid sodium as coolant)

Power Reactors

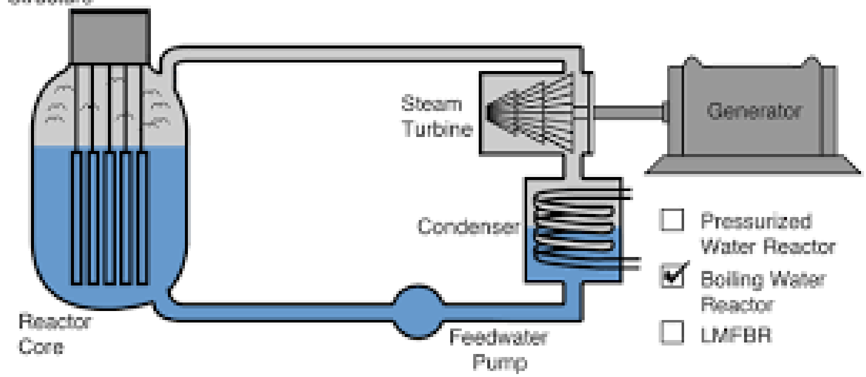
Based on the operating pressure:

- Pressurized water reactor.
- Boiling water reactor.



Thickness and Design Pressure of Some Common Reactor Pressure Vessels

Reactor Type	Operating Pressure (MPa)	Operating Pressure (PSI)	Wall Thickness (mm)	Wall Thickness (in.)
PWR	15.5	2,250	225	8.86
BWR	7.15	1,050	150	5.90
CANDU	10.0	1,450	30	1.20
HTGR	5.0	725	25	1.00
AGR	4.3	625	4,700	158.05
LMFBR	~0.1	15.0	5,800	228.35



Power Reactors

Based on the neutron energies:

- Thermal reactor.
- Fast reactor.

Based on the moderator:

- Graphite-moderated.
- Water-moderated.

Power Reactors

Based on the capability to produce more fuel than they consume:

- Breeder reactor.
- Consume reactor.

Natural Abundance of Various Nuclear Fuels in the Earth's Crust

Isotope	Classification	Natural Abundance	Half-Life (Years)	Created from
U-233	Fissile	Does not exist in nature	159,200	Th-232
U-235	Fissile	0.71%	703,800,000	N/A
U-238	Fertile	99.4%	4.468 billion years	N/A
Pu-239	Fissile	Does not exist in nature	24,100	U-238
Pu-241	Fissile	Does not exist in nature	14	Pu-239

Design Parameters for Some Common Reactor Cores

Reactor Type	Fuel Assembly Geometry	Type of Fuel	Rod Pitch (mm)	Coolant	Moderator	Fuel Rod Length (m)
PWR	Square	Enriched UO_2	12.60	H_2O	H_2O	3.88
BWR	Square	Enriched UO_2	14.37	H_2O	H_2O	4.09
CANDU	Concentric circles	Natural UO_2	14.60	D_2O[a]	D_2O	0.49
HTGR	Hexagonal block	Enriched UO_2	23.00	He	Graphite	0.79
AGR	Concentric circles	Enriched UO_2	37.00	CO_2	Graphite	1.04
LMFBR	Hexagonal	PuO_2	9.80	Liquid Na	Not used	2.70

Power Reactors

Design Parameters of a Modern Nuclear Power Plant (by Reactor Size or Type)

Feature	PWR	BWR	CANDU PWR (HWR)	AGR	LMFBR
Coolant (primary loop)	Light water	Light water	Heavy water	Carbon dioxide	Liquid sodium
Pressure (primary loop) (MPa/PSI)	15.50 (2,250)	7.15 (1,040)	10 (1,450)	4.25 (615)	~0.1 (20)
Temperature (primary loop)[a]	330°C	293°C	310°C	640°C	540°C
Coolant (secondary loop)	Light water	N/A	Light water	Light water	Light water
Pressure (secondary loop) (MPa/PSI)	6.9 (1,000)	N/A	4.7 (680)	17.0 (2,450)	17.5 (2,500)
Temperature (secondary loop)[a]	285°C	N/A	260°C	545°C	490°C
Type of fuel	Enriched uranium	Enriched uranium	Natural uranium	Enriched uranium	Uranium and plutonium
Average enrichment	4%–5%	3%–4%	0.71%	~3%	~15%–20% Pu
Fuel assembly shape	Square	Square	Concentric circles of rods	Concentric circles of rods	Hexagonal
Cladding	Zircaloy-4	Zircaloy-2	Zircaloy-4	Stainless steel	Stainless steel
Moderator	H_2O	H_2O	D_2O	Graphite	None
Classification	Thermal converter	Thermal converter	Thermal converter	Thermal converter	Fast breeder
Thermal efficiency	34%	32%	29%	42%	40%
SGs	Yes	No	Yes	Yes	Yes
SG type	U tube	N/A	U tube	Helical coil	Helical coil
Core power density (kW/L)	105	52	12	2.7	~400
Average burnup (MWD/ton)	50,000	50,000	7,500	20,000	110,000

Source: Todreas, N. and Kazimi, M.S. *Nuclear Systems*, Vol. 1, CRC Press, Boca Raton, FL (2008).

[a] Temperatures shown are the maximum average loop temperatures.

Thank You

Stay safe!