Contents

1. Basics

1.1 What is Nuclear Science?

- It is study of structure, properties, and interactions of atomic nuclei at fundamental level.
- A molecule consists of atoms. An atom consists of a nucleus.
- **Nucleus→** which carries almost all the mass of the atom and a positive charge (Proton), surrounded by a cloud of electrons.
- **Nuclei** →consist of: **protons and neutrons**, also called **nucleons**.
- **Atomic number**→the number of protons (z) in atom is the **atomic number** of an element.
- **Atomic mass** of the element →the number of protons and neutrons in an atom.
- Number of electrons in an atom = number of protons in an atom (normally)
- **Isotopes**
  - Atoms of the same element which contains the same number of protons but different number of neutrons.
  - They have same chemical properties but slightly different physical properties.
  - Example:
    - Carbon-12 (6 protons+ 6 neutrons)→stable
    - Carbon-14 (6protons+ 8 neutrons)→ unstable

- It is the electrons that are responsible for the chemical behavior of atoms, and which identify the various chemical elements.
- Uranium, for instance, has three isotopes occurring in nature – 238U, 235U and 234U.
- Hydrogen has 3 types of isotopes- Protium, Deuterium and Tritium.

1.2 Radioactive decay

- Most of the isotopes which occur naturally are stable.
- A few naturally occurring isotopes and all of the man made isotopes are unstable.
- The unstable isotopes can become stable by releasing different types of particles. The process→ **radioactive decay**
- elements which undergo this process→ **radioisotopes**
- The product of this decade →**daughter isotopes**

Alpha decay

$$^{235}_{92}U \longrightarrow {}^{231}_{90}Th + {}^{4}_{2}He$$

Beta decay

$$^{235}_{92}U \longrightarrow {}^{235}_{93}Np + {}^{0}_{-1}e$$

Gamma decay

$$^{235}_{92}U \longrightarrow {}^{231}_{92}Th + {}^{0}_{0}Y$$

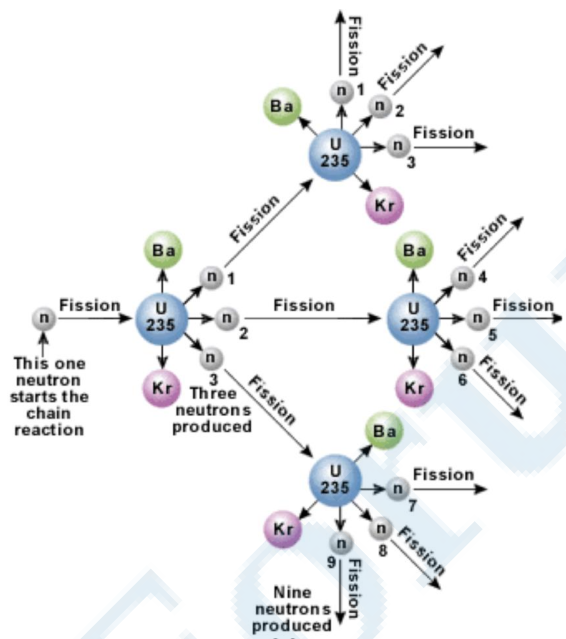
- **Alpha decay**
  - Produces a helium 4 nucleus →**alpha particle.** The daughter nucleus contains two fewer protons and two fewer neutrons than the parent. Observed in nuclear with atomic mass greater than 200.

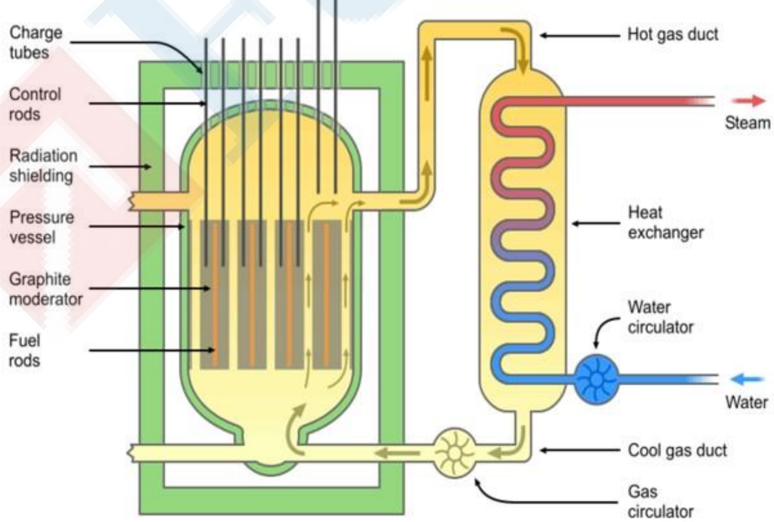
- **Beta decay**
  - Observed in nuclear that have a large number of neutrons. Neutron is split into a proton and a high energy electron→ beta particle the latter of which is ejected from the nucleus.
- **Electron capture**- the opposite of beta emission. The capture of the electron allows a proton to turn into a neutron.
- **Gamma decay -**
  - When atoms decay by emitting alpha or beta particles to form a new atom, the nuclei of the new atom formed may still have too much energy to be completely stable. These items will emit gamma rays to release that energy.
  - Gamma rays are high energy radiation
  - Gamma rays are not charged particles like alpha and beta particles.
    There is no change in mass or atomic number.

1.3 Nuclear fuel

- **Nuclear fuel** is any material that can be consumed to derive nuclear energy.
- **Yellow cake→** The solid form of mixed uranium oxide, which is produced from uranium ore in the uranium recovery (milling) process. The material is a mixture of uranium oxides.
- **Fertile element →** it is an isotope that is not itself fissile but can be converted into a fissile material. example- Th-232, 238U
- **Fissile element** (nuclide that is capable of undergoing fission after capturing low –energy neutrons)→uranium-235. The most common nuclear fuels are 235U and 239Pu. Not all nuclear fuels are used in fission chain reactions.
- **Nuclear enrichment→** the nuclear fuel used in a nuclear reactor needs to have a higher concentration of the U235 isotope than that which exists in natural uranium ore. U235 when concentrated (or "enriched") is fissionable.
- **Depleted uranium→** the metal remaining after uranium-235 has been extracted from uranium. It is a heavy metal, used in munitions, e.g., in armor-piercing weapons.
- **Critical mass→** it is the smallest amount of fissile material needed to undergo a nuclear chain reaction.
- **Transmutation→** it is a process that involves a change in the nucleus of an atom. When the number of protons in the nucleus of an atom changes, the identity of that atom changes as it is turned into another element or isotope. It can be either natural or artificial. (E.g. Uranium converting to plutonium).

- **Fuel rods**
  - A long, slender, zirconium metal tube containing small portion of fissionable material, which provide fuel for nuclear reactors.
  - Fuel rods are assembled into bundles called fuel assemblies, which are loaded individually into the reactor core.
- **Chain reaction**
  - A nuclear chain reaction occurs when the output of one reaction causes more reactions to occur.
  - These chain reactions are almost always a series of **fission** events, which give off excess neutrons. It is these excess neutrons that can go on to cause more fission events to occur. Hence a chain reaction takes place.





2. Nuclear power reactors

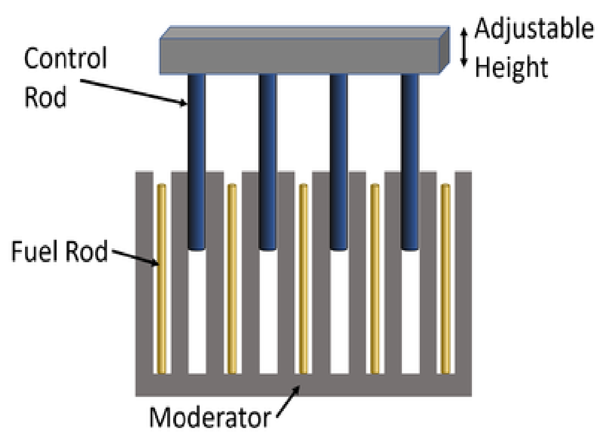
A nuclear reactor is a device in which nuclear chain reactions are initiated, controlled, and sustained at a steady rate.

2.1 Working

Working of a fission reactor

- **Nuclear fission** creates heat.
- **Nuclear fission reactor→** the main job of a nuclear fission reactor is to house and control nuclear fission—a process where atoms split and release energy.
- Reactors use **uranium** for **nuclear fuel**.
- The uranium is processed into small ceramic pellets and stacked together into sealed metal tubes → **fuel rods.**
- Typically more than 200 of these rods are bundled together to form a fuel assembly.
- **Reactor core**
  - **A reactor core** is typically made up of a couple hundred assemblies, depending on power level.
  - Inside the reactor vessel, the fuel rods are immersed in water which acts as both a coolant and moderator.
- **The moderator**
  - Neutron released in the chain reaction moves extremely fast which might lead to unstable chain reaction. To slow down the speed of the neutron moderators are used.
  - Moderators are atoms which does not take neutron and usual have lighter nuclei.
  - **Example** of moderator - heavy water, light water and graphite.

- **Control rods→**
  - One of the neutrons released from uranium fission is used to produce another fission reaction. Another neutron is absorbed by control rods.
  - Though neutrons are absorbed by control rods, discharge of energy doesn't takes place.
  - Uranium-235 fission releases 2.5 neutrons on average, but only one neutron is needed so the control rods absorbs extra neutron.
  - Examples: chemical elements such as boron, cadmium, silver, hafnium, or indium, that are capable of absorbing many neutrons without themselves fissioning.



- **Critical mass**→the minimum amounts of uranium-235 required to set up the chain reaction- **critical mass.**
- The heat created by fission turns the water into steam, which spins a turbine to produce carbon-free electricity.

2.2 Types of fission reactors.

Thermal Reactors	Fast Neutron Reactors
Thermal reactors uses slowed or thermal neutrons to keep up the fission of their fuel.	Fast neutron reactors use fast neutrons to cause fission in their fuel

2.3 Types of Nuclear fission reactors

The pressurized water reactor (PWR)

- The PWR uses regular water as a **coolant.**
- The primary cooling water is kept at very high pressure so it **does not boil**.
- In a PWR, the primary coolant (water) is pumped under high pressure to the reactor core where it is heated by the energy generated by the fission of atoms.
- The heated water then flows to a steam generator where it transfers its thermal energy to a secondary system where steam is generated and flows to turbines which, in turn, spin an electric generator.
- Pressure in the primary coolant loop prevents the water from boiling within the reactor.

Heavy water reactor

- Uses **heavy water (deuterium oxide D2O)** → coolant and neutron moderator.
- The heavy water coolant is kept under pressure, allowing it to be heated to higher temperatures without boiling, much as in a pressurized water reactor.
- Heavy water acts as a good moderator. But unlike water, is does not absorb the neutrons. So this allows natural uranium to be used in nuclear power plants.

Breeder reactor

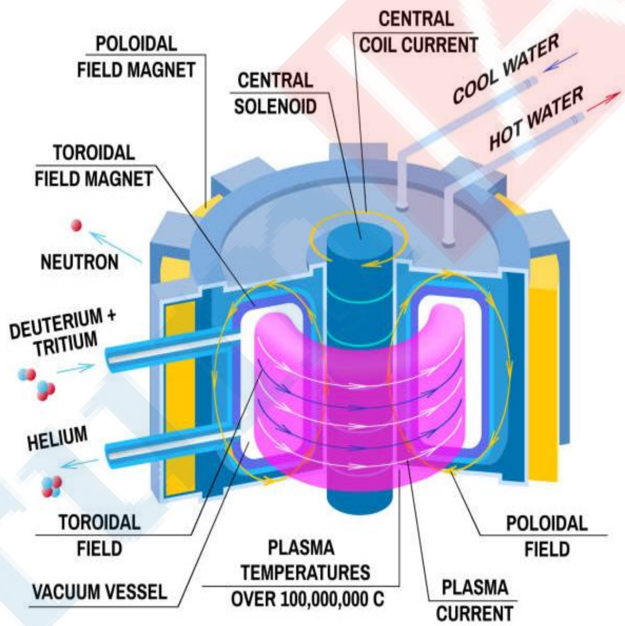
- Designed for breeding, a breeder reactor produces more fissile material than they consume during the fission chain reaction. However, an initial stock of fissile material is required.
- Ex- It converts fertile U-238 to Pu-239, or Th-232 to U-233.
- Types of breeder reactors- liquid-metal cooled fast breeder-reactor (LMFBR), gas-cooled fast breeder-reactor (GCFR), molten salt breeder reactor, light water breeder reactor.

A Fast Breeder Reactor (FBR)

- It is a nuclear reactor that uses fast neutron to generate more nuclear fuels than they consume while generating power dramatically, enhancing the efficiency of the use of the resources.
- Fast neutrons are not as effective at causing fission; they are instantly captured by U-238 to become plutonium Pu-239.
- It produce more fuel than they consume hence the production of plutonium is maximized. (Pu-239 is formed)

3. Fusion reactors

3.1 Plasma



- At extreme temperatures, electrons are separated from nuclei and a gas becomes plasma.
- It is an ionized state of matter similar to that of gas.
- It is composed of charged particles (positive nuclei and negative electrons)
- Fusion plasmas provide the environment in which light elements can fuse and yield energy.

3.2 Working of the fusion reactor

- Fusion reaction takes place under a nuclear fusion reactor to produce energy.
- **Raw material** for fusion- Tritium isotope of hydrogen which has two neutrons, deuterium is an isotope of hydrogen which has one neutron and plasma.
- The fusion reactor will heat a steam of deuterium and tritium fuel to form high temperature plasma. It will squeeze the plasma so that fusion can take place.
- The lithium blankets outside the plasma reactions chamber will absorb high energy neutrons from the fusion reaction to make more tritium fuel. The blankets will also get heated by the neutrons.
- The heat will be transferred by a water cooling loop to a heat exchanger to make steam.
- The steam will drive electrical turbines to produce electricity.
- The steam will be condensed back into water to absorb more heat from the reactor in the heat exchanger.

3.3 ITER (international experimental reactor/ artificial sun experiment)

International thermonuclear experimental reactor /artificial sun experiment. (ITER)

- Announced in June 2005, it is being built in the South of France at the Cadarache site. **India signed its agreement in 2005**
- **Objective→** to demonstrate the possibility of producing commercial energy from nuclear fusion.
- Seven partners who will contribute to build ITER. Each one of them will built their own share of ITER components through an appropriately formed domestic agency DA and industries and finally deliver them to ITER.
- India's contribution was about 10% of the ITER construction cost.
- **Tokamak** – An experimental machine designed to harness the energy of fusion.

Tokamak → it is an experimental machine designed to harness the energy of fusion. The energy produced through the fusion of atoms is absorbed as heat in the walls of the vessel. Fusion power plant uses this heat to produce steam and then electricity by way of turbines and generators.

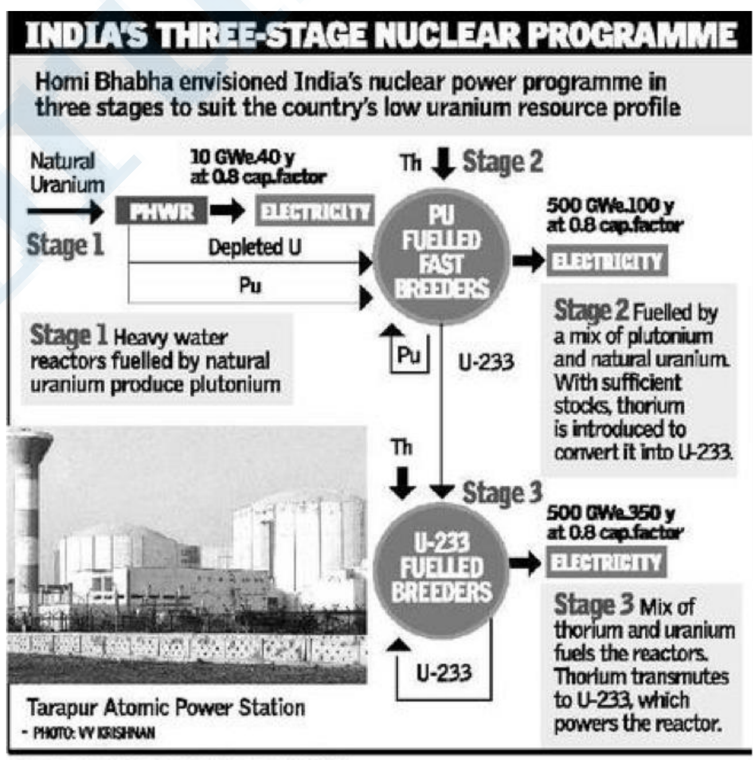
3.4 Nuclear fission v/s fusion

	fission	Fusion
Definition	Fission is the splitting of a large atom into two or more smaller ones.	Fusion is the fusing of two or more lighter atoms into a larger one.
Natural occurrence of the process	Fission reaction does not normally occur in nature.	Fusion occurs in stars, such as the sun.
Byproducts	Fission produces many highly radioactive particles.	Few radioactive particles are produced by fusion reaction.
Energy Requirement	Takes little energy to split two atoms in a fission reaction.	Extremely high energy is required to bring two or more protons close enough that nuclear forces overcome their electrostatic repulsion.
Energy Released	The energy released by fission is a million times greater than that released in chemical	The energy released by fusion is three to four times greater than the energy released by

	reactions, but lower than the energy released by nuclear fusion.	fission.
Nuclear weapon	One class of nuclear weapon is a fission bomb, also known as an atomic bomb or atom bomb.	One class of nuclear weapon is the hydrogen bomb, which uses a fission reaction to "trigger" a fusion reaction.
Energy production	Fission is used in nuclear power plants.	Fusion is an experimental technology for producing power.
fuels	Uranium is the primary fuel used in power plants.	Hydrogen isotopes (Deuterium and Tritium) are the primary fuel used in experimental fusion power plants.
Applications	• Nuclear power plant • Control rods • Atomic bombs	• Electricity • Abundant fuel supply. • Fusion reactors.

4. India's three stage civil nuclear power programme

In 1954 Baba confirmed the 3 stage plan for the country's development. It was formally adopted by Indian government in 1958. Thorium was recognized as a source capable for providing power to the country



Source: Department of Atomic Energy website

First stage

- **Fuel**- natural uranium
- **Reactor**- pressurized heavy water reactor **(PHWR)**
- **Moderator**- D2O (heavy water)
- **Coolant**- D2O heavy water
- Pressurized heavy water reactors which are fueled with natural uranium generate electricity during the first stage of the programme which generates plutonium 239 as a byproduct.

Second stage

- **Fuel** –plutonium (with oxides of Uranium)
- **Reactor**- FBR fast breeder reactor
- **Moderator** -not in use
- **Coolant**- liquid sodium
- **Fuel**: A mixed oxide consisting plutonium 239 (recovered by re processing spent fuel at the 1st stage, and natural uranium);
- **Working**: Plutonium-239 experiences fission, producing energy; Mixed oxide fuel carrying uranium 238 transforms intro extra plutonium -239; Hence, the stage 2 FB's are intended to breed additional fuel than their consumption;

Third stage

- **Fuel-** thorium (with oxides of plutonium, uranium)
- Reactor -Advanced heavy water reactor (**AHWR**) and thermal breeder reactor.
- **Moderator**- light water demineralized water
- **Coolant-** D2O heavy water
- **Fuel**: Stage 3 nuclear reactors consist of thorium-232 - uranium-233;

5. Nuclear Weapons Control

PTBT: Partial Test Ban Treaty (PTBT)

- Banned Nuclear Weapon Tests under water, atmosphere and Outer Space; except those conducted underground;
- Baruch Plan(1946, Harry Truman); Standstill agreement(1954);
- Result: 499 tests conducted between 1945 to 1963; 433 over next decade of PTBT;
- Conference of disarmament: PTBT negotiations for CTBT;

NPT 1968: Non-Proliferation Treaty

- Objectives:
  - Non proliferation - Prevent spread of nuclear weapon and technology;
  - Peaceful use;
  - Disarmament- general and complete disarmament;
- **Nuclear weapons state**: US, UK, Russia, France, China - built and tested before 1 January 1967
- **Members: 191 states** are party to it. **Never Accepted**: India, Israel, Pakistan and South Sudan
- **Review** every 5 years; Treaty **extended indefinitely, 1995;**
- **Nuclear safety umbrella:** NPT, IAEA, NSG, CTBT**;**

CTBT (1996)

- Comprehensive Nuclear-Test-Ban Treaty (CTBT): bans nuclear weapons test explosions for both civilian and military purposes, in all environments.
- **Status**: Adopted by UNGA is 1996; Not in force(44 annex 2 nations, 8 have not ratified it);
- **Monitoring**: CTBTO

Intermediate range nuclear forces treaty

- Between the US and Russia;
- Banned all of the two nations' land-based ballistic missiles, cruise missiles, and missile launchers with ranges of 500–1,000 kilometers (short medium-range) and 1,000–5,500 km (intermediate-range);
- Did not apply to air- or sea-launched missiles; United States withdrew from the Treaty on 2nd August 2019.

Fissile material cut-off treaty:

- Fissile Material is any material which can be used to create a Nuclear Bomb;
- It includes high enriched uranium and plutonium;

IAEA

- **Objective**: Promoting peaceful use, implementing safeguards, promoting nuclear safety
- Established independently of the United Nations through its own international treaty, the IAEA Statut; IAEA reports to both UNGA and UNSC.

Miscellaneous

- **MECR**: informal group of like minded suppliers; Aim: non-proliferation of WMD; control list of exports and national guidelines;

NSG:

- Multilateral export control regime; founded in response to the Indian nuclear test in May 1974; London club; Trigger list – IAEA;
- **Aim**: Prevent nuclear proliferation by controlling the export of materials, equipment and technology;
- China is a member, India is not;

Wassenaar Arrangement

- Export Controls for Conventional Arms and Dual-Use Goods and Technologies

Australia Group

- Check spread of chemical and biological weapons; Uniform list of 87[4] compounds;

Missile Technology Control Regime (MTCR)

- Proliferation of missiles and missile technology;
- Focus on rockets and unmanned aerial vehicles capable of delivering a payload of at least 500 kg (1,100 lb) to a range of at least 300 km;

6. Governance Structure

Apex board: Atomic Energy Commission of India

Regulatory Board: Atomic Energy Regulatory Board (**AERB**), Mumbai, Maharashtra

Public Sector

- Uranium Corporation of India, Singhbhum
- Nuclear Power Corporation of India (NPCIL), Mumbai, Maharashtra
- Bharatiya Nabhkiya Vidyut Nigam Limited (**BHAVINI**), Kalpakkam, Tamil Nadu

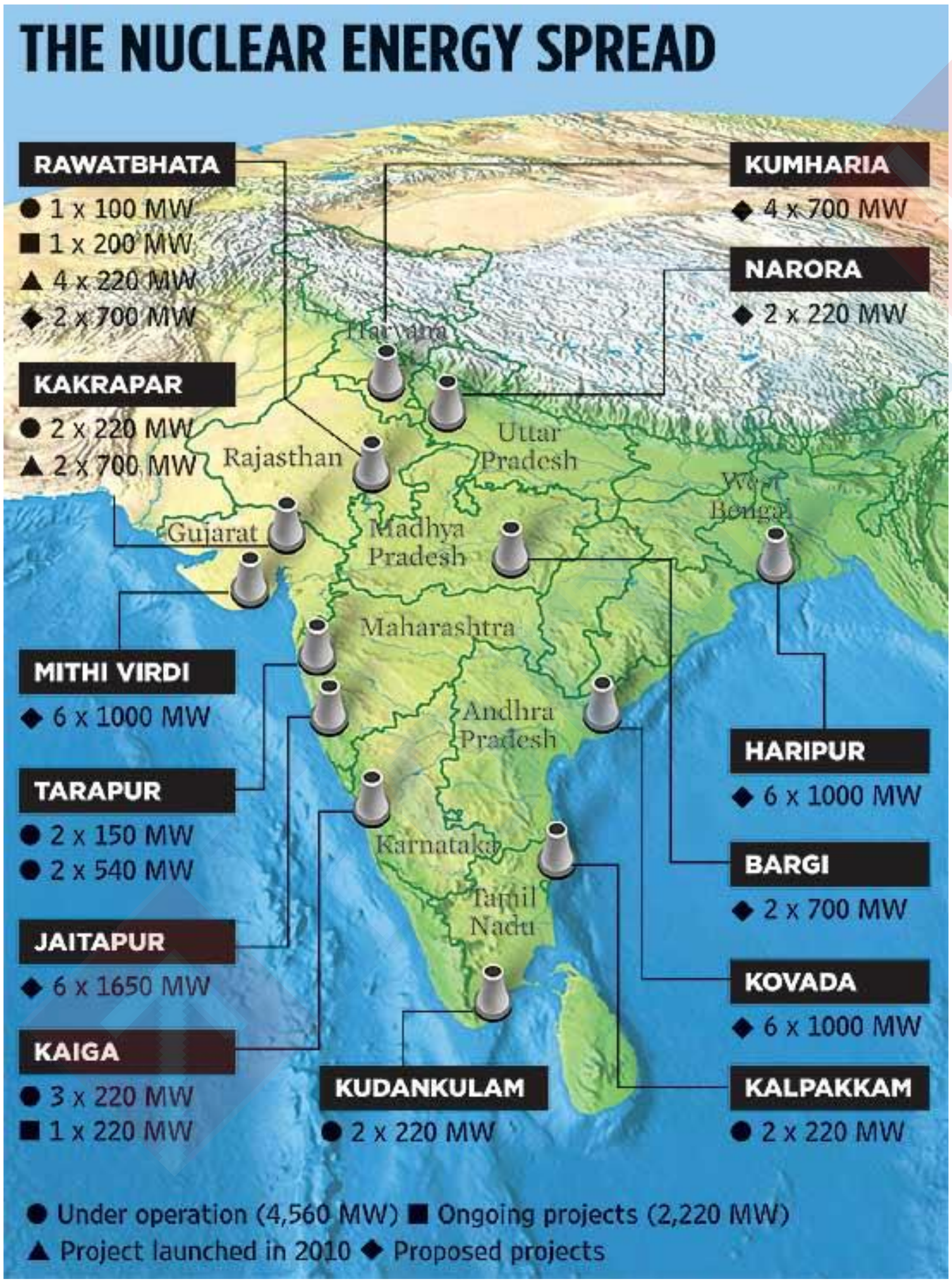
Research centres

- Bhabha Atomic Research Centre (**BARC**), Mumbai
- Indira Gandhi Centre for Atomic Research (**IGCAR**), Kalpakkam (Tamil Nadu)
- Atomic Minerals Directorate for Exploration and Research (**AMD**), Hyderabad.

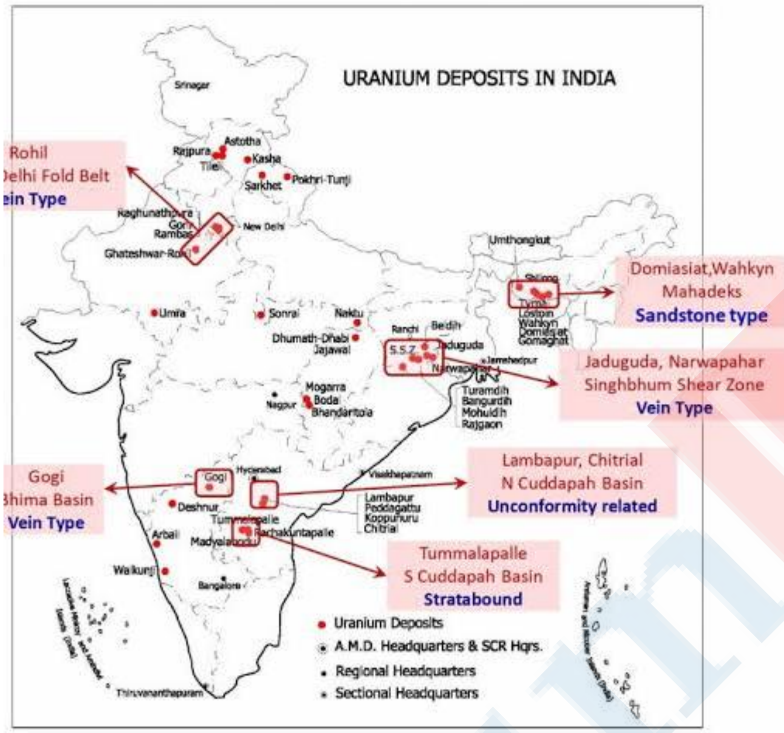
Industrial Organisations

- Nuclear Fuel Complex (**NFC**), Hyderabad

7. Nuclear Power Plants



8. Fuel Reserves



SPACE FOR NOTES

SPACE FOR NOTES