# TARGET PRELIMS 2024
# BOOKLET-3; S&T-3
# NUCLEAR SCIENCE AND TECHNOLOGY

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## 2. NUCLEAR SCIENCE AND TECHNOLOGY

### 1) NUCLEAR ENERGY BASICS

- What is nuclear energy?
  - Nuclear energy is the **energy in the nucleus of an atom** which is released during nuclear fission or fusion reaction.
  - During these reactions, a small amount of **mass is lost and gets converted** into energy according to Einstein's equation.
    - In **nuclear fission**, the nucleus of a heavy atom (such as uranium, plutonium or thorium), when bombarded with low - energy neutrons, can be split apart into lighter nuclei.
    - When this is done tremendous amount of energy is released, if the mass of the original nucleus is just a little more than the sum of the masses of the individual products.
- E.g. of fission reaction

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\ ^{1}_{0}n$$

Pu (239, 94) + n (1,0) -> Ba (145, 56) + Sr (92,38) + 2 n(1,0)

In a nuclear fission, the difference in mass, $\Delta m$, between the original nucleus and the product nuclei gets converted to energy $E$ at a rate governed by the famous equation,

$$E = \Delta m\, c^2,$$

first derived by Albert Einstein in 1905, where $c$ is the speed of light in vacuum. In nuclear science, energy is often expressed in units of electron volts (eV): 1 eV = 1.602 $\times$ $10^{-19}$ joules. It is easy to check from the above equation that 1 atomic mass unit (u) is equivalent to about 931 mega electron volts (MeV) of energy.

- **E.g. of fusion reaction**

$$4\ ^{1}_{1}H \rightarrow ^{4}_{2}He + 2\ ^{0}_{+1}e$$

  - This is one of the common reactions taking place in sun.

### 2) FUSION REACTION (THERMONUCLEAR REACTIONS)

- **Introduction:**
  - **Fusion** is the energy source of the Sun and Stars.
    - At very high temperature and pressure in the core of the stars, hydrogen nuclei collide and fuse to convert into **heavier helium atoms** and release **tremendous amount of energy** in the process.
  - What is the **need of extremely high temperature** -> to **overcome the electrical repulsive force**

- Till date we don't have any stable fusion reaction.
    - **Development of thermonuclear energy power plants has been difficult:**
    - **Three conditions must be fulfilled** to achieve fusion in a laboratory:
        - **Very High Temperature** (of the order of 15 million degrees C)
        - **Sufficient Plasma particle density** (to increase the likelihood that collisions do occur)
        - **Sufficient confinement time** (to hold the plasma, which has the propensity to expand, within a defined volume)

- **Note:** Twentieth century fusion science identified the most efficient fusion reaction in the laboratory setting to be reaction between two hydrogen isotopes, deuterium (D) and tritium (T), as the D-T reaction produces the higher energy gain at the "lowest temperatures".

- **Why nuclear fusions are important as an energy source?**

    - Raw material easily available

    - Nuclear Fusion is a clean and green route to produce energy, as it doesn't involve any remnant waste products.

    - Long term energy security

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## A) USA'S ATTEMPT:

- In Dec 2022, an experiment at US National Ignition Facility (NIF), within the Livermore National Laboratory, Livermore, California, achieved a **fusion ignition** by successfully conducting a fusion test that produced 153% (**1.53 gain**) as much energy as went into triggering it.

- In July 2023, in a repeat of the above experiment, scientists were able to generate **more energy** with nearly a **factor of 2 in gain** compared with energy of the incoming lasers.

- **Types of Fusion Reactions:**
    - For fusion reaction to happen in reactors, the high temperature must be **created artificially**. There are **two different ways** of achieving this: **Inertial Confinement Method** and **Magnetic Confinement Method**:
        1) **Inertial Confinement Method**: In this method, high energy laser beams are focused onto a pellet of the fuel (**D-T**), which creates extreme temperatures required for fusion inside it. The outer mass of the pallet explodes and is responsible for confining the reaction.
            - E.g., **The NIF reactions**
        2) **Magnetic Confinement Fusion** (MCF): It uses a magnetic field to contain plasma, which prevents the particles from hitting the reactor walls which could otherwise cause them to slow down.
            - **Magnetic confinement** uses a torus-shaped reactor called **tokamak**, in which a hydrogen plasma is heated to a high temperature and the **nuclei are guided by strong magnetic fields to fuse**. **ITER** is a famous example of an experiment trying to achieve fusion using magnetic confinement.

- This is the method being user at ITER.

3) **Some other variants** also exist such as those which use a combination of these methods (**Magnetized Target Fusion)** and those that combine fission with fusion (**Hybrid Fusion**)

- **The NIF Breakthrough**:
  - In **Dec 2022**, NIF was finally able to achieve '**breakeven', or** a net positive energy gain.
  - **In July 2023**, it was able to replicate its efforts, but now with a bigger gain (almost 2)
  - In both these achievements **inertial confinement was employed**.
    - In NIF's set up, high-power lasers fire pulses at a 2 mm wide capsule inside a 1-cm-long cylinder called **hohlraum,** in less than 10 billionths of a second. The capsule holds deuterium and tritium atoms.
    - As the pulse strikes the hohlraum's inside, the latter heats up and releases x-rays, which **heat the nuclei to millions of degrees centigrade** and compress them to **billions of Earth atmosphere**. This **technique is called inertial confinement method** because the nuclei's inertia creates a short window between implosion and explosion in which the strong nuclear force dominates, fusing the **nuclei**.
    - Specifically, when two hydrogen-2 nuclei fuse, they yield a helium-4 nucleus, a neutron and **17.6 MeV** of energy.

- **Significance:**
  - **Fusion ignition** is one of the most impressive feats of the 21st century and is an engineering marvel beyond belief.

- **Some Caveats:**
  - **First:** NIF experiment is highly sophisticated and required very high precision. Even small changes in the experiment may negatively impact the output. So, for long term use, **they will have to reproduce these results again and again.**
  - **Second**: For fusion reaction to be truly gainful, the **energy released by the reactions needs to be greater than the energy going into the lasers**, about 300 megajoules, and not just the energy delivered to the hohlraum. This hasn't been achieved yet. The energy transferred to plasma is just 1%, the rest is all lost in other processes. "**Future research will need to focus on reaching the next major milestone – a target gain of G > 100**, which is required to run a power plant efficiently.
  - **Third**: The road to a power plant from the NIF's current achievement isn't well understood.

## B) ITER (INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR (ITER)

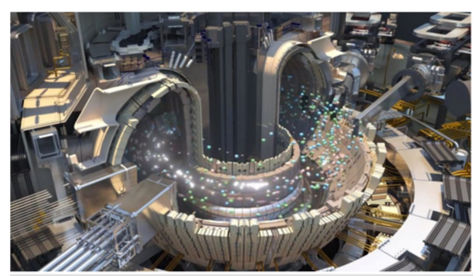
- ITER is an international mega project which is aimed at creating nuclear energy through nuclear fusion reaction.
- **35 countries** are collaborating to build the **world's largest tokamak**, a magnetic fusion device that has been designed to prove the feasibility of fusion as a large scale and carbon free source of energy.

- The **primary objective** of the ITER is the investigation and demonstration of **burning plasma** – plasmas in which the energy of the helium nuclei produced by the fusion reactions is enough to maintain the temperature of plasma, thereby reducing or eliminating the need of external heating.

- **What will ITER do?**
  - » Achieve a deuterium-tritium plasma in which the fusion conditions are sustained mostly by internal fusion heating (**"burning plasma"**).
  - » Generate **500 MW** of fusion power in plasma.
  - » **Demonstration of the integrated operation of technologies** for a fusion power plant (superconducting magnets, remote maintenance, and systems to exhaust power from the plasma)
  - » **Test tritium breeding** – One of the missions for the later stages of ITER operation is to demonstrate the feasibility of producing tritium within the vacuum vessel.
  - » **Demonstrate the safety characteristic of a fusion device**.
    - ITER achieved an important landmark in fusion history when, in 2012, the ITER Organization was licensed as a nuclear operator in France based on the rigorous and impartial examination of its safety files.
    - One of the primary goals of ITER operation is to demonstrate the control of the plasma and the fusion reactions with negligible consequences to the environment.

- **India** is also participating in ITER. PM Modi while participating in the ITER assembly said that the ITER is perfect example of the age-old India belief – **Vasudhaiva Kutumbakam** – the entire world is working together for the betterment of humankind and that India stands proud with its fair share of contributions to the cooling water, cryogenic and cry-distribution systems, auxiliary heating devices using RF and beam technologies.

## C) WHAT IS A TOKAMAK:



- The Tokamak is an experimental machine which is designed to harness the energy of a fusion. Inside a tokamak, the energy produced through the fusion of atoms is absorbed as heat in the walls of the vessel. (Heat -> steam -> rotate turbine)

- First developed by Soviet research in the late 1960s, the tokamak has been adopted around the world as the most promising configuration of magnetic fusion device. **ITER will be the world's largest tokamak**—twice the size of the largest machine currently in operation, with ten times the plasma chamber volume.

- **How does Tokamak Work -> Class discussion** (not very important for exam)

## D) INDIA AND FUSION

- India has become one of the major players in fusion technology and has been one of the pioneers in its development.
- The **Plasma Physics Program** was initiated by the GoI in 1982 to conduct research at MCF, which later evolved into the **Institute for Plasma Research (IPR)** in 1986 and led to the creation of India's own **tokamak, ADITYA**, in 1989.

- Subsequently, it also developed a large semi-indigenous tokamak called the **Steady State Superconducting Tokamak** (SST-1) which was fully commissioned in 2013. IPR has also revealed its plans for a successor, the SST-2.

- In 2005, India became the 7th member to join the **International Thermonuclear Experiment Reactor (ITER) project**, a global initiative attempting to build the world's largest tokamak reactor.
    - **ITER-India** has been set up under the supervision of IPR and is responsible for fulfilling India's commitment to the project. It has already provided the world's largest **cryostat**, a vacuum application stainless steel vessel, to house the reactor, along with a host of other equipment.

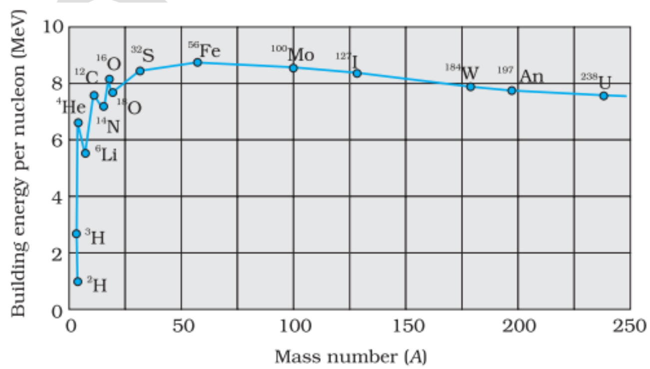
- **Key Limitations for India:**
    - Lack of **Private Investment**: it is primarily because of Atomic Energy Act, 1962, which puts the brunt of developing and running nuclear power stations on the government.
    - **However**, a recent government panel convened by NITI aayog has recommended overturning the ban of foreign investment and allowing greater participation of private players.

## 3) NUCLEAR BINDING ENERGY

The Nuclear mass M is always less than the mass of neutrons and mass of protons in the nucleus.

This **mass defect** will explain the energy required for breaking a nucleus containing protons and neutrons into individual protons and neutrons.

Similarly, if certain number of neutrons and protons are brought together to form a nucleus of certain charge and mass, an energy $E_b$ will be released in the process. This energy $E_b$ is called the **binding energy of the nucleus** (**Or Nuclear Binding Energy)**.




## 4) COMPONENTS OF NUCLEAR POWER REACTOR

- **Components of Nuclear Fission Reactor**

  - **Fuel:** Uranium is the basic fuel. Usually pallets of **Uranium Oxide ($UO_2$)** are arranged in tubes to form fuel rods.

  - **Neutron Source:** 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 another alpha emitter**. Alpha particles from the decay cause a release of neutrons from the beryllium as it turns to carbon-12. Restarting a reactor with some old fuel may not require this, as there may be enough neutrons to achieve criticality when control rods are removed.

  - **Moderator:** Material in the core which slows down the neutrons released from fission so that they cause more fission. It is usually water but may be heavy water or graphite.

- **Control Rods:** These are made of neutron absorbing material such as Cadmium, Hafnium or Boron, and are inserted or withdrawn from the core to control the rate of reaction.
- **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.
- **Steam Generator:** Part of the cooling system of pressurized water reactors (PWRs and PHWRs) where the high-pressure primary coolant bringing heat from the reactor is used to make steam for the turbine, in a secondary circuit.

## 5) TYPES OF REACTORS

### A) BOILING WATER REACTOR

### B) PRESSURIZED WATER REACTOR

### C) PRESSURIZED HEAVY WATER REACTOR

### D) ADVANCED GAS COOLED REACTORS

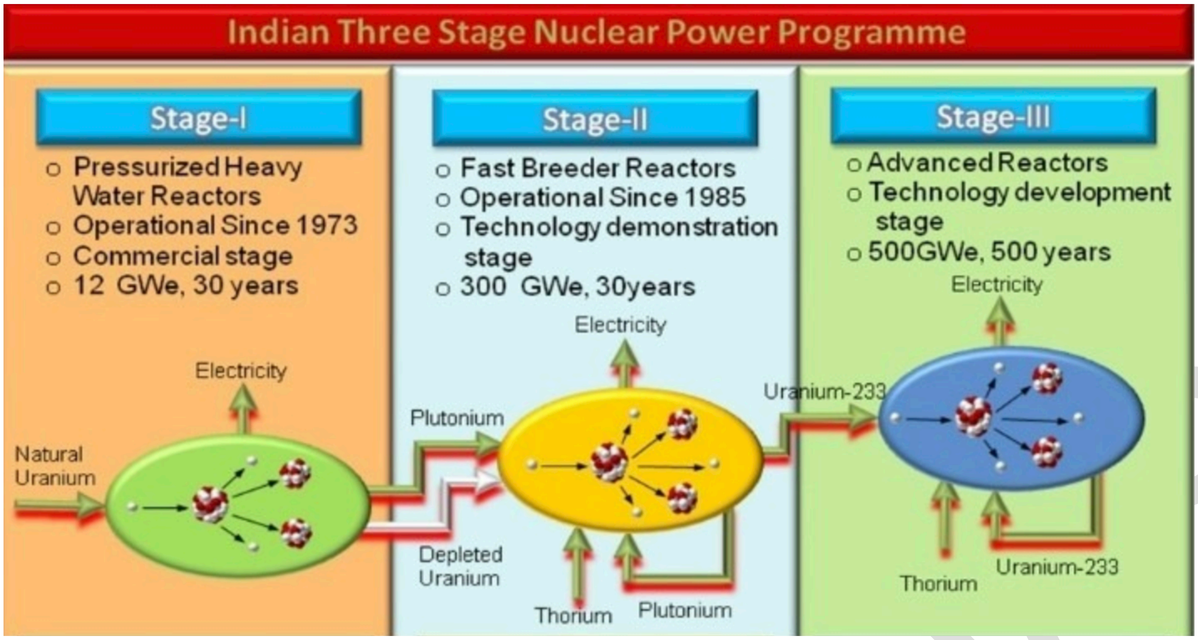
### E) FAST NEUTRON REACTOR (FAST BREEDER REACTOR)

- Some reactors (**only one in commercial service**) do not have a moderator (they use a coolant that is not effective moderator, like liquid sodium). Although these fast neutrons are not good at causing fission, they are readily captured by uranium ($U_{238}$), which then becomes plutonium ($Pu_{239}$). This Plutonium isotope can be reprocessed and can be used as more reactor fuel or in the production of nuclear weapons.

- **Advantages:**
    - They get more than 60 times as much energy from the original Uranium compared with normal reactors.
    - Reduction in radioactive waste.
    - Safety -> closed fuel cycle would ensure safety
    - Energy security for India -> India plans third phase of its nuclear energy program on the success of FBR
- **Disadvantage:** Expensive and complicated to build and operate
- **Fast Breeder Reactors -** If FNRs are configured to produce more fissile material (plutonium) than they consume they are called Fast Breeder Reactors (FBR).
    - Breeder reactors are possible because of the proportion of uranium isotopes that exist in nature.
- **Problems associated with fast Breeder reactors / Fast Neutron Reactors**
    - Plutonium produced can be removed and used in nuclear weapons
    - To extract Plutonium the fuel must be reprocessed, creating radioactive waste and potentially high radiation exposure.
- **Use scenario globally**
    - US, UK, France and Germany have effectively shut down their fast breeder reactor plants
    - **India, Russia, Japan and China** currently have operational fast breeder reactor program.

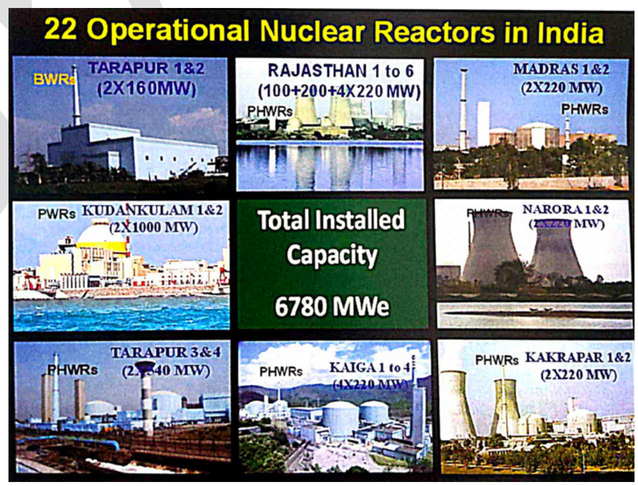
## 6) INDIA'S 3-STAGE NUCLEAR POWER PROGRAM

- The three-stage nuclear power production program of India had been conceived by the 'father of Indian Nuclear Power Program' Dr Homi J Bhabha, with the ultimate objective of utilizing the country's vast reserves of thorium-232.
    1. The first stage comprises setting up of **Heavy Water Reactors**/**Pressurized Heavy Water Reactors (PHWRs)** and associated fuel cycle facilities.
    2. The second stage envisages setting up of **Fast Breeder Reactors (FBRs)** backed by reprocessing plants and plutonium based fuels fabrication plants. Plutonium is produced by irradiation of U-238.
    3. The third stage is based on **the thorium-232 -> Uranium 233 Cycle**, Uranium-233 is obtained by irradiation of Thorium.

- 


- ==**Progress of the 3 Stages**==

    - **The first stage** of Nuclear Power Programme is already in **commercial domain**. The Nuclear Power Corporation of India Ltd. (NPCIL), a public sector undertaking of DAE, is responsible for the design, construction and operation of nuclear reactors. The company presently operates 23 reactors with a capacity of **7.8 GW**. In addition, the company is also engaged in construction of many other nuclear power reactors. In addition, 10 nuclear power reactors with a total of 8000 MW capacity are under construction. This include a 500 MW PFBR of the second stage nuclear power program. Further, government has accorded administrative approval and financial sanction of 10 indigenous PHWRs of 700 MW capacity each, to be set up in fleet mode. With completion of these projects, **India's nuclear energy capacity is expected to go to 22.4 GW by 2031**.




| Nuclear power plant | State | Reactor |
|---|---|---|
| Tarapur atomic power station | Mha | Taps-1; taps-2<br>2*160 mw (BWR)<br>Taps-3 and taps-4<br>(2*540) (phwr) |
| Rajasthan atomic power station | Rajasthan | Raps-1 to 6<br>(100 + 200 + 4*220) |
| Madras atomic power station | Tn | Maps-1; maps-2<br>(2*220) (phwrs) |
| Kaiga atomic power station | Karnataka | Kaps-1 to 4 |

| | | |
|---|---|---|
| | | (4*220) (phwrs) |
| Kakrapara atomic power station | Gujarat | Kaps-1, kaps 2<br>(2*220) (phwrs)<br>**Kaps-3 (generating electricity from 30th Aug 2023)<br>(700MW)<br>Kaps-4 (attained criticality in Dec 2023)** |
| Kudankulam nuclear power plant | Tn | Kknpp-1; kknpp-2<br>(2*1000 mw) pwrs |
| Naora atomic power stations | Uttar pradesh | Naps-1; naps-2<br>(2*220 mw) (phwrs) |

- **Karappar-3** has been generating commercial electricity from 30th Aug 2023.
    - **The 700 MWe** units are the largest indigenous nuclear power reactors to be built by the Nuclear Power Cooperation of India (NPCIL), a public sector undertaking of the Department of Atomic Energy (DAE)
- **Kakrapar-4** (KAPP-4), with 700 MWe capacity, started controlled chain reaction and thus became **critical in Dec 2023**.
- Both these reactors are PHWRs, which use natural Uranium as fuel and heavy water as coolant.

- **The Second Stage** of Nuclear power generation programme is geared towards setting up the Fast Breeder Reactors. These reactors produce more fuel than they consume. The fast breeder program is in **technology demonstration stage**.
    - **Features of the Prototype Fast Breeder Reactor (PFBR)**
        - **Fuel:** Plutonium Uranium Oxide ($PuO_2$ and $UO_2$)
        - **Coolant:** Liquid Sodium
        - **Liquid Sodium additional safety requirements**
            - Since sodium explodes if it comes in contact with water and burns when in contacts with air, additional safety requirements are needed to isolate the coolant from the environment.
            - Sodium also absorbs neutron to form Radioactive $Na^{24}$ isotope.
        - **Advantages of FBR:**
            - They can ensure upto 60 times as much energy from the original Uranium compared with normal reactors.
            - Reduction in radioactive waste.
            - Safety -> closed fuel cycle would ensure safety
            - Energy security for India -> India plans third phase of its nuclear energy program on the success of FBR

- **The Third Stage:** of the Nuclear Power Programme is in **technology development stage**.
    - The ongoing development of 300 MWe Advanced Heavy Water Reactor (AHWR) at BARC aims at developing expertise for thorium utilization and demonstrating advanced safety concepts.
    - Thorium-based systems such as AHWR can be set up on commercial scale only after a large capacity based on fast breeder reactors, is built up.
    - Why Thorium based reactors are important for us
        i. **Abundance:** India has the world's third largest reserve of thorium.
        ii. **Less Enrichment requirement:** Thorium mining produces a single pure isotope, whereas the mixture of natural uranium isotope must be enriched to function.
        iii. **Superior Nuclear Properties:** Superior physical and nuclear properties
        iv. **Better Nuclear weapon resistant:** Better resistance to nuclear weapon proliferation
            - Weapon grade fissionable material (U-233) is harder to retrieve safely from a thorium reactor. It contains U-232, a strong source of gamma radiation that makes it difficult to work with. Further, its daughter product, thallium-208, is equally difficult to handle and easy to detect.
        v. Reduced plutonium and actinide production. They have miniscule long lived radioactive waste.

## 7) THORIUM RESERVES IN INDIA

- As per the Department of Atomic Energy, **India has reserves of thorium in sufficient quantity** as compared to other parts of the world.
- As of 2014, the Atomic Mineral Directorate for Exploration and Research (AMD), a constituent unit of Department of Atomic Energy (DAE), has so far established 11.93 million tonnes of in situ resource **Monazite** (Thorium bearing mineral) in the country which contains about 1.07 million tonnes of thorium.
- **The state-wise details of the Monazite resources** (as of March 2021, as per Department of Atomic Energy):
    » **Total: 12.73 million tonnes of Monazite** (More than 1 million tonnes of thorium in it)

| State | No of Deposits | Resource (million tonne) | |
|---|---|---|---|
| | | Monazite | Total Heavy Minerals |
| Odisha | 12 | 3.16 | 332.44 |
| Andhra Pradesh | 24 | 3.78 | 333.45 |
| Tamil Nadu | 50 | 2.47 | 298.42 |
| Kerala | 35 | 1.84 | 242.88 |
| Maharashtra | 5 | 0.004 | 5.64 |
| Gujarat | 2 | 0.07 | 12.53 |
| West Bengal | 1 | 1.20 | 5.45 |
| Jharkhand | 1 | 0.21 | 1.12 |
| Total | 130 | 12.73 | 1,231.93 |

## 8) OTHER IMPORTANT ASPECTS

- **Why most of the nuclear power plants are situated near the coast?**

- **India's n-facilities under IAEA's umbrella (Dec, 2014)**
  - Paving the way for import of fuels for its nuclear reactors, India has completed the process of placing its civilian reactors under IAEA safeguards.
    - The reactors under the IAEA's umbrella are eligible to use imported uranium.
  - **Need of placing reactors under IAEA safeguards**
    - Enable India to use international fuel for civilian reactors.
  - A deal was signed under which India was to sign and ratify the **Additional Protocol of the IAEA**. A separation plan was chalked out after the deal, segregating the military and civilian reactors.

## 9) NUCLEAR WASTE MANAGEMENT

- **Global Endeavours for Nuclear Waste Management:**
  - » **On Site Storing:** Some nations go for onsite storing. But it carries the risk of **radioactive leakage**.
  - » In USA, for e.g., spent fuel is stored in a concrete and steel container called a dry cask.
  - » **India and a few other countries**, reprocess about 97-98% of spent fuel to recover plutonium and uranium. India also recovers materials like caesium, strontium, and ruthenium, which finds application as blood irradiators to screen transfusions, cancer treatment, and eye cancer therapeutics, respectively. The remaining 1-3% end up in storage facilities. India also immobilizes the wastes by mixing them with glass, which is kept under surveillance in storage facilities.
  - » **Deep geological Repositories:** Nations like Finland, Canada, France and Sweden are looking at deep geological repositories to tackle spent nuclear fuel wastes.
    - In Jan 2022, the Swedish government greenlit an underground repository for nuclear waste. Construction in Sweden will take at least 10 years.

  - » **About Onkalo Spent Nuclear Fuel Repository**: It is a deep geological repository for the final disposal of spent nuclear fuel. It will be **world's first long-term disposal facility** for spent fuel.
    - **Is geological repository safe?**
      - Experts associated with the project said that 40 years of theoretical and lab-based studies suggest that the geological repository is **safe**.
      - The bedrock provides a natural barrier to protect from radioactive release to the environment, such as water bodies and air.
      - The use of copper and clay provides a protective layer to ensure no release due to extreme conditions like earthquakes.

### A) FUKUSHIMA AND THE ISSUE OF ITS WASTE DISPOSAL

- **Why in news?**
  - » In Aug 2023, in spite of backlash from public and neighbouring countries, Japan began the release of contaminated water from the Fukushima nuclear plant into the sea (Aug 2023)

- **Project to decommission the facility**:
  - » The decommissioning project got cabinet's approval in 2021 and could take three decades to complete. It will cost $76 billion. Under this Japan **plans to start flushing 1.2 million tonnes of water from the embattled nuclear power plant** into the Pacific Ocean.
  - » **Issue of water disposal into the Pacific Ocean:**
    - ▫ The water that the Japanese government wants to flush from the plant was used to cool the reactor, plus rainwater and groundwater. **It contains radioactive isotope from the damaged reactor** and is thus itself radioactive. Japan has said that it will release this water into Pacific over the next 30 years.
    - ▫ **Why release water in ocean?**
      - o TEPCO is running **out of room for the water tanks** and that nuclear plants around the world regularly release water containing trace number of radionuclides into large water bodies.
    - ▫ **How was the water treated?**
      - o The Tokyo Electric Power Cooperation (TEPCO) has treated the water using multiple techniques**, notably the Advanced Liquid Processing System (ALPS)**, which removes 62 types of radioactive material.

- » **CONCERNS:**
  - o **ALPS** technique doesn't remove **Tritium** which can be easily absorbed by the bodies of living creatures and rapidly distributed via blood. Removing tritium is quite impossible as it is chemically similar to Hydrogen. Sice tritiated water can pass through the placenta, it could lead to developmental effects in babies when ingested by pregnant women.
    - ▪ Though Japanese government argue that the concentration of tritium doesn't exceed international standards, in particular, those of IAEA. It is six times less than the limit of tritium in drinking water.
    - ▪ As per TEPCO, the radiation emitted by Tritium is "extremely weak, and can be blocked with a single sheet of paper".
  - o There is **no safe limit of radionuclide** and any number of radionuclides in water will increase the risk of cancer.
  - o **Neighbouring countries** like China, South Korea and Taiwan have also expressed concerns over Japan's Plan

## 10) CLND, 2010

- This act has been deemed responsible for Nuclear energy deadlock within the country. The two most contentious have been **Section 17(b) and Section (46)**

- **Section 17(b) :** It contains provisions on **recourse liability on suppliers**. This allows a liable operator to recover compensation from a supplier in case the accident was caused by provisions of sub-standard services or defective or faulty equipment.
- **Section 46:** Potentially unlimited liability under this section. Section 46 provides that *nothing would prevent proceedings other than those which can be brought under the act, to be brought against the operator*. This is not uncommon as it allows criminal liability to be pursued where applicable.

## 11) NUCLEAR BOMB:

**Basic Raw material for atomic bomb**

- An atomic bomb can be made from two types of radioactive materials: Uranium and Plutonium. In both cases, the manufacturing starts with Uranium ore.
- **Highly enriched U-235** (more than 90%) and no control rod to extract neutrons.
  - **Uranium** mined from earth is less than 1% U-235, the isotope that can be used to fuel reactors and make bombs. Centrifuges are needed to separate the U-235 from the rest of the Uranium, in a process called **Enrichment**. Bomb grade Uranium 90% U-235.
  - The Other fuel that can be used to make a bomb, **plutonium,** is made by irradiating uranium in a nuclear reactor. The process transforms some of the Uranium into Plutonium.

### A) UNDERESTIMATED FALLOUT OF THE TRINITY NUCLEAR TEST: NEW STUDY (JULY 2023)

- On 16th July 1945, in a nuclear test code named "**Trinity**", a plutonium-based implosion device was set off a 100-foot metal tower. The irradiated mushroom cloud also went many times higher into the atmosphere than expected – Some 50,000 to 70,000 feet.
- **New Findings**: Using state of art modelling software and recently uncovered historical weather data, the study found that radioactive fallout from the Trinity test reached **46 states, Canada and Mexico** within 10 days of detonation. How much of the fallout still remains is difficult to calculate.

### B) J ROBERT OPPENHEIMER: FATHER OF ATOM BOMB

- **Why in news?**
  - » Christopher Nolan's new film on the American Physicist who built most destructive weapon known to man was released on 21st July 2023.

- **J Robert Oppenheimer** (1904-1967) was an American physicist and one of the most prominent scientists of 20th century. He is best known for his role as the **scientific director of the Manhattan Project**, the top-secret US government program during WW-II that led to the **development of the first atomic bomb**.
- **Education**: He was born in 1904, in New York City. He attended Harvard University and studied Physics there. He completed his **PhD in theoretical physics at University of Gottingen in Germany** under the supervision of Max Born in 1927. Later he returned to USA, and taught in University of California,

Berkely, and the California Institute of Technology (Caltech). He made significant contribution to physics, especially in the area of quantum mechanics and quantum field theory, earning him the recognition as one of the leading theoretical physicists of his time.

- In **1942**, he was appointed as the scientific director of the **Manhattan Project**. He played a crucial role in organizing and coordinating the efforts of various scientists and engineers to develop an atomic bomb. The project resulted in successful detonation of the **first atomic bomb on 16th July 1945**, in the New Mexico desert, in an area known as the **Trinity Test Site**.
- **The use of Atomic Bomb** over Hiroshima and Nagasaki in Aug 1945 led to the end of WW-II and raised profound ethical and moral questions about the use of nuclear weapons. Oppenheimer was **deeply affected** by the destruction caused by the bombs and became an **advocate for arms control and international cooperation in the peaceful use of atomic energy**.
- **His political views** and opposition to nuclear weapons led to him coming under **scrutiny during the era of McCarthyism and the Red Scare**. In 1954, his **security clearances were removed**, and he was also **ostracized from the scientific community**.
- Inspite of these controversies, he continued serving at Princeton from 1947 – 1966. In 1963, he received the Enrico Fermi Award, one of the highest honors in the field of nuclear science.
- He passed away in 1967, leaving behind a complex legacy of a brilliant physicist and a controversial figure in American History.

It was **only in 2022**, that the US government nullified its 1954 decisions, and affirmed his loyalty. President Joe Biden's Energy Secretary, **Jennifer M Granholm**, said the decision to revoke Oppenheimer's clearance was the result of a "flawed process", and that with time more evidence of his loyalty and love of country have only been further affirmed.

## 12) NUCLEAR ENERGY AND ENERGY SECURITY

- **Introduction:**
  - » Energy security means consistent availability of sufficient energy in various forms at affordable prices. When a country moves ahead on the path of development, it is necessary to utilize every energy resource available in the country.
  - » Currently, nuclear energy makes up about 3% of India's energy sources
  - » **Advantages of Nuclear Energy:**

    a) **Least carbon footprint** (lesser than renewable energy)

    b) **Cost of nuclear powe**r

    c) **Quantity of waste generated** is also very less

    d) **Potential of self sufficiency**

    e) **Depleting fossil fuels and import dependency**: India is currently drawing around 63% of its total energy from thermal sources. A significant part of this is imported.

f) **Limitations of Renewable Energy**

- Renewable energy are subject to vagaries of weather; they are land intensive; dependence on import technology; energy storage handicaps;
- Renewable energy is inevitable and nuclear option should be retained as insurance.

» **Limitations**

a) Safety concerns in light of recent disasters

b) Nuclear waste disposal is a big concern

c) Potential of developing nuclear weapons

d) Security concerns

e) India is dependent on other countries both for raw material and technology

f) Ecological concerns

g) Long gestation period

h) More safeguards -> more costly

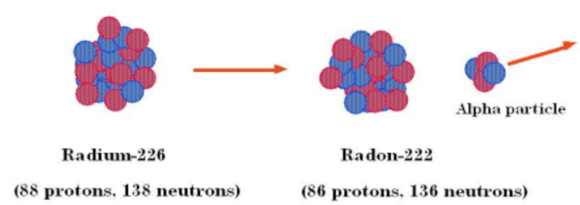
## 13) RADIOACTIVITY BASICS

- **Introduction**

  - Radioactivity is the tendency of unstable nuclei to emit particles in order to bring it closer to stability. There are four main types of radioactivity.

1. **Alpha Radiation**: The emission of a He nucleus.

   Alpha radiation is common when the nuclides of high atomic mass have a **lower neutron to proton ratio** than stable nuclide and ejects an alpha particle.




2. **Beta Minus (plus) radiation**: the emission of a high energy electron (or positron) from the nucleus.

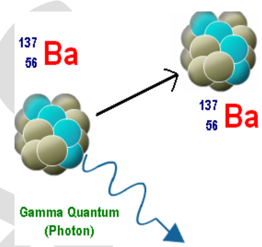
   - Generally, an unstable atomic nucleus with an excess neutron undergo **Beta (-) decay**, where a neutron is converted into a proton, an electron and an electron anti-neutrino (the antiparticle of the neutrino).

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

- An unstable atomic nucleus with an excess of protons may undergo beta (+) decay, also called **positron decay**, where a proton is converted into a neutron, a positron, and an electron neutrino.

$$p \rightarrow n + e^{+} + v_e$$

3. **Gamma Radiation**: These are penetrating electromagnetic radiation of a kind arising from radioactive decay of atomic nuclei.




   - The decay of an atomic nucleus from a high energy state to a lower energy state, a process called gamma decay, produces gamma radiation.
   - Gamma rays ionize atoms, and are thus biologically hazardous.

4. **Neutron Radiation**: It is a kind of ionizing radiation that consists of free neutrons.
   - This is generally a result of nuclear fusion and nuclear fission reaction.

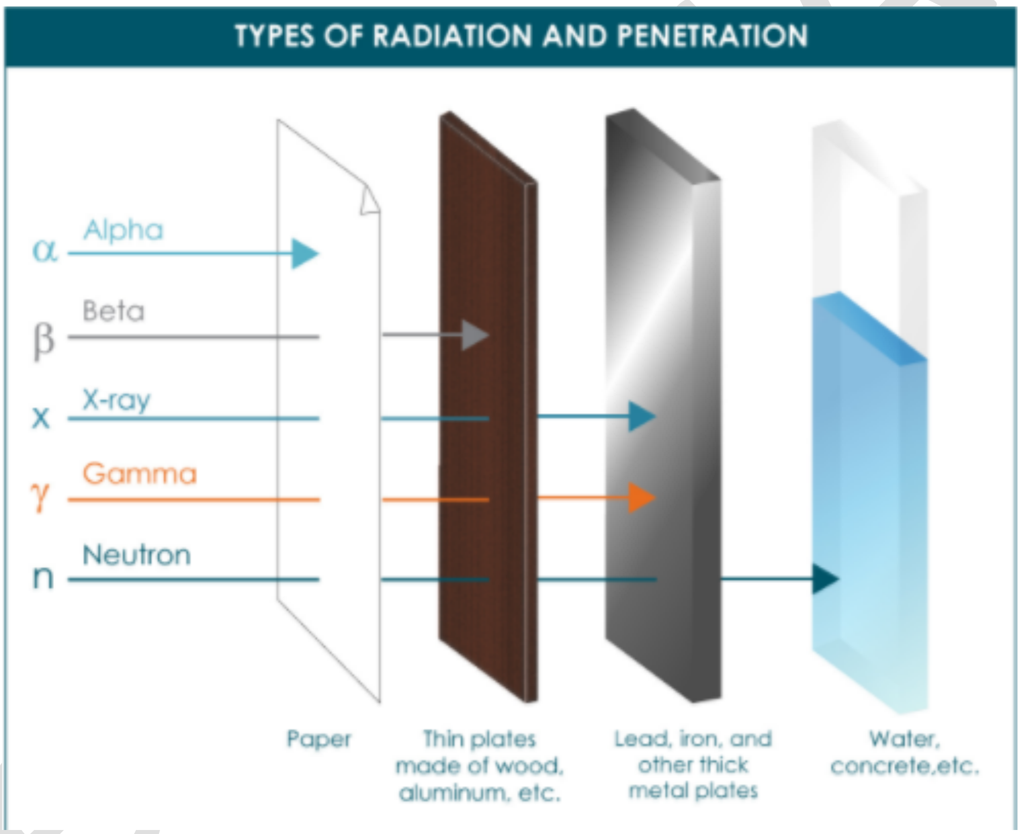
- These particles (Alpha, Beta and Gamma) are available at an extremely low level in nature. Moderate to high rates of exposure to these particles can be severely detrimental to organic tissues and the life threatening to humans and rest of the ecosystem.

- **Radiation can be ionizing or non-ionizing**, depending on how it affects matter.
  - **Non-ionizing radiation** includes visible light, heat, radar, microwaves, and radio waves. This type of radiation deposits energy in the material through which it passes, but it doesn't have sufficient energy to break molecular bonds or remove electrons from atoms.
  - **Ionizing Radiation** (such as x-rays and cosmic rays) is more energetic than non-ionizing radiation.
    - When ionizing radiation passes through material, it deposits enough energy to break molecular bonds and displace (or remove) electrons from atoms. This electron displacement creates two electrically charged particles (ions), which may cause changes in the cells of plants, animals, and people.
    - Ionizing radiation can be used for a number of beneficial purposes.

- For e.g. ionizing radiations are used in smoke detectors, medical purposes, etc.

- **Level of penetration of various ionizing radiations (**see the adjacent figure**)**

- **Sources of Radioactivity**
  - Minerals containing naturally radioactive elements (potassium, radium, uranium, thorium…)
  - Background cosmic rays
  - Solar Flux




  - Nuclear power plants and nuclear fuel cycle plants
  - Old Equipment (e.g. watches and clocks having radio luminescent paints) (radium, tritium)
  - Nuclear labs
  - Radioactive waste
  - Nuclear Medicines
  - Nuclear Bomb testing
  - Radon gas

## 14) RADIOACTIVE DECAY

- Radioactive decay is the process through which radioisotopes lose their radioactivity over time. This gradual loss of radioactivity is measured in half-lives.
- **Law of Radioactive Decay:**
  - In any radioactive sample, which undergoes α, β or γ-decay, it is found that the number of nuclei undergoing the decay per unit time is proportional to the total number of nuclei in the sample. If N is the number of nuclei in the sample and ΔN undergo decay in time Δt then
  - $\Delta N / \Delta t \propto N$
    or, $\Delta N/\Delta t = \lambda N$
- The **activity of a radioactive nucleus** (the rate of decay with time) can be described by the following equation:

$$A = \frac{dN}{dt} = -\lambda N$$

where λ is the 'decay' constant of the process in the equation.

- The **half-life** of a radioactive material is the time it takes one-half of the atoms of a radioisotope to decay by emitting radiation.
  $T_{1/2} = \frac{ln2}{\lambda}$ (note: ln2=0.6931)
  - The half-life of different elements can range from fractions of a second (for radon-220) to millions of years (for thorium 232).
  - **Note:** Half Life of Carbon-14 is **5,730** years.

## 15) RADIO-CARBON DATING

- Radiocarbon dating is a method by which age of an object is determined using radiocarbon, a name for the isotope Carbon-14.
- **How is Carbon-14 formed?**
  - It is created in the earth's atmosphere when cosmic rays – energetic streams of charged particles coming from sources in outer-space – slam into the atoms of the gases and release neutrons. When these neutrons interact with the nitrogen-14 nitrogen isotope, they can **produce carbon-14**. Since cosmic rays are constantly passing through earth's atmosphere, the carbon-14 is getting constantly created.
  - Carbon-14 readily combines with atmospheric oxygen to from **radioactive CO2** which enter the bodies of plants (during photosynthesis), animals (when they consume plants), and other biomass through the carbon cycle.
  - **Two key things which makes carbon-14 dating accurate**:

- **The concentration of carbon-14** in the earth's atmosphere doesn't change across thousands of years. (if this wasn't true than radiocarbon dating – which dates organic materials by measuring the amount of carbon-14 they contain-wouldn't work.
- **Carbon-14**, in the form of carbondioxide and other carbon compounds, would have to be able to diffuse into the earth's various ecosystems such that the **concentration of carbon-14 in the atmosphere** was comparable to the concentration of carbon-14 in the planet's other biospheres.

- **How does radiocarbon dating work?**
  - **When an organism is alive**, it constantly exchanges carbon with its surrounding by breathing, consuming food, defecating, shedding skin etc. Through these activities, carbon-14 is **both lost and replenished** in the body, so its **concentration in the body is nearly constant and in equilibrium with its surrounding**.
  - **When the living organism dies**, the C-14 is not replenished and it begins to **reduce due to radioactive decay**.
  - **Radiocarbon dating** dates an object by measuring amount of C-14 left, which scientists can use to calculate how long ago the body expired.

- **Note:** Since carbon-14 decays with a half-life of around **5,730 years**, its presence can be used to date samples that are **around 60 millennia old (**i.e. 60,000 years old**)**. Beyond that, the concentration of carbon-14 in the sample would have declined by **more than 99%**.

- **Tools of Radiocarbon dating**:
  - **Geiger Counter** was used in 1940s when radiocarbon dating began. It consists of a **Geiger-Muller tube** connected to some electronics that interpret and display signals.
    - The Geiger-Muller tube contains **a noble gas, such as helium or neon**, and a rod passing through the centre. A high voltage is maintained between the tube's inner surface and the rod. The gas is insulating, so no current can pass between the two. But when energetic particles (including gamma radiation), such as those emitted during radioactive decay, pass through the gas, they can energize electrons in the gas's atoms and produce an electric discharge. The persistent voltage could also encourage these electrons to knock off electrons in more atoms, producing a bigger discharge (**called the Townsend discharge**). This electric signal is relayed to the electronics, where, say, a light may come on in response, indicating that radioactive decay is happening nearby.

  - **Today**, more sophisticated devices are used. For e.g., one of the most sensitive dating setups uses **accelerator mass spectrometry (AMS),** which can work with organic samples as little as 50 mg.
    - **Mass spectrometry** is used to isolate ions that have the same mass-to-charge ratio. They begin with a sample – for e.g. a piece of bone – bombard it with electrons to ionize the atoms. Then they subject ions to different physical conditions that cause them to separate according to their **mass-to-charge ratio**.
      - **For e.g. when deflected by electric or magnetic fields** – Ions with different mass-to-charge ratios are deflected to different extents.

- **Impact of Radio-carbon dating on science and technology**: It was the first objective dating method to give numerical date to organic matter. Its impact on the field of archaeology and geology have come to be known as "**radiocarbon revolution"**

## 16) USE OF NUCLEAR RADIATION TECHNOLOGY FOR PROVIDING BETTER QUALITY OF LIFE TO ITS CITIZENS

1. **Health: Care to Cure**

   - Healthcare has grown into one of the most important peaceful uses of nuclear energy.
   - **Nuclear Medicine - Diagnosis**
     - Radio pharmaceuticals can be administered by injection, inhalation, or orally and selectively localized and retained at sites of diseases. And thus, allow an image to be obtained of the loci using **gamma scintigraphy** or to deliver cytotoxic dose of radiation to specific disease sites without adversely affecting the surrounding normal tissues.
     - They help in identification of abnormalities in organ function even in early stages of a disease.

   - **Radiation Therapy**
     - A treatment that involve use of high-energy radiation either by using special machines or from radioactive substance. The aim is to impart specific amount of radiation at tumours or parts of the body to destroy the malignant cells.

       1. **External Beam Radiation Therapy / teletherapy**
          - Radiation is delivered by using a machine outside the body.
          - A machine, either a $^{60}$Co-teletherapy unit or linear accelerator is used
          - It can be used to treat Breast Cancer, Bowel Cancer, Head and Neck Cancer and Lung Cancer.
          - **Bhabatron** is a teletherapy machine developed by BARC and has been installed in 50 cancer hospitals.
            - It is cheaper than any imported telecobalt machine.

       2. **Internal Radiation Therapy or brachytherapy**
          - Radioactive material is placed in the body near cancer cells.
          - It makes it possible to treat a cancer with a larger dose of radiation that can't be given with external beam radiation therapy.

- Tiny titanium encapsulated Iodine-125 seeds have been developed by BARC and have provided an avenue to treat eye cancer.

2. **Food Security (1. Nuclear Agriculture 2. Food Preservation 3. Assessing the quality of output )**

- Use of ionizing radiation based technologies provide **safe hygienic and economically viable** solutions to address issue of agricultural productivity

1. **Nuclear Agriculture**

   - Ionizing radiation is being used by BARC to **induce mutation** in plant breeding, and 42 varieties of different crops have been released to Indian farmers for commercial cultivation in the country.
     - e.g. groundnuts, mungbean, blackgram, pigeon pea, cowpea, mustard etc.
   - Advantages
     - Higher yield
     - Earliness
     - Large seed size
     - Resistance to biotic and abiotic stress

2. **Food Preservation - Produce and Preserve**

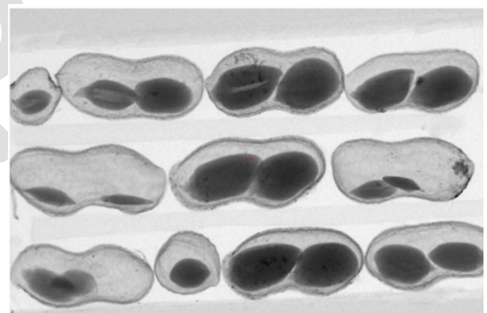
   - Almost 30% of the food produced in India is lost due to spoilage because of pest attack, contamination and moulds infestation. These are encountered both during harvesting as well as post-harvest handling storage of the edible and cash crops.
   - **Limitation of using pesticides**
     - Health hazards
     - Disturbance to ecology
     - Development of resistance in pest
   - **Radiation Processing** can provide a viable, effective, and eco-friendly alternative to chemical fumigants and microbial decontamination, as the latter affect human health and environment adversely.
   - There is an utmost need to adopt and integrate the irradiated foods into the country's supply chains and promote the widespread use of this technology to ensure food safety and security.
   - **Advantages of using radiation processing**

- Disinfestation of insects, pests in cereals, pulses and grain.
- Microbial decontamination (hygienization) of dry species etc. for preservation/shelf life extension by applying pre-determined radiation doses.
- Increasing the exportability of Indian food produce.
- Elimination of parasites and pathogens of public health importance in food
- Delay in ripening and senescence in fruits and vegetables
- Inhibition of sprouting in tubers, bulbs and rhizomes

▪ **Radiation in no ways make production radioactive**.

- Radiation therapy has been approved by WHO, IAEA, WTO, FSSAI etc.
- As per the Department of Atomic Energy, as of Dec 2022, there are 25 irradiation facilities operational in the country in private, semi-government and government sector for food preservation.

3. **X-Rays to assess the quality of food crops**:



- Portable X-Ray imaging system can be very useful in grain value chains where the time needed to assess the economic value of grain by threshing or milling is a significant barrier.
  - » For e.g., a team comprised of scientists from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad and the Fraunhofer Development Center for X-Ray Technology (EZRT) in Erlangen, Germany have for the first time used **x-Ray radiography to determine key market-related traits of peanuts** while still inside the hull. (Sep 2022)

- X-Ray Radiography has the potential to be the right technology for in-field evaluation of farmers' produce which the International Committee for Food Value and Safety calls for.

**3. Energy Security - Nuclear is Clean and Green**

**4. Societal Application: Sludge Hygenisation - from waste to wealth**

5. **Hydrogel - Healing the wound**

▪ The process was developed by BARC scientists and technologically has been transferred for commercial purpose.

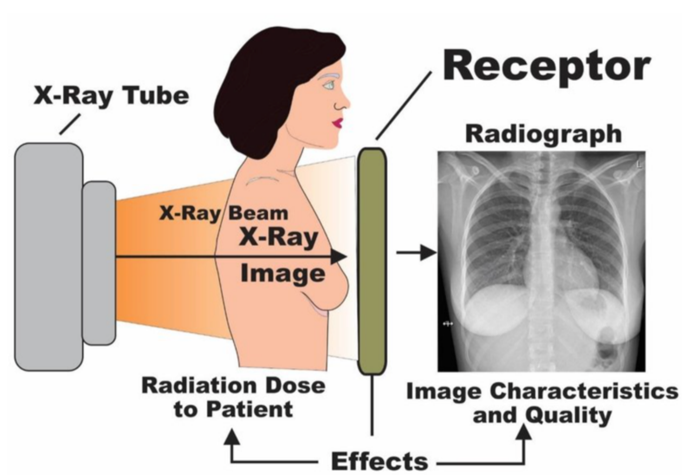
- Hydrogel is a thin transparent sheet of gel and is an excellent medical tool particularly useful for burn and injury dressings.
- **Production**
  - It is prepared by cross linking molecules of hydrophilic polymers like PVA either chemically or by Gamma/Electron beam irradiation.
  - A 3D network of gel like structure is formed which holds large quantities of water. Gamma Irradiation achieves gel formation and sterilization in one step.

6. **Water Resources**
   1. **Isotope Hydrology techniques**
   2. **Measuring contaminants in water**

7. **Industrial Applications**
   1. **Radiation Sterilization of Medical Products**
   2. **Radiography**
      - Radioisotopes which emit gamma rays are more portable than x-ray machines, and may give higher-energy radiation, which can be used to check welds of new gas and oil pipeline systems, with the radioactive source being placed inside the pipe and the film outside the weld.
      - Radiography can also be used to gauge the thickness and density of materials or locate components that are not visible to other means.

## 1) X-RAY RADIOGRAPHY

- **X-Ray Radiography:** X-Ray radiography uses **very small amount of ionizing radiation to produce pictures of the body's internal structure**. These are amongst the oldest and most frequently used form of medical imaging. They are often used to help diagnosed fractured bones, look for injury or infection and to locate foreign objects in soft tissues.




  » **How does it function?** During a radiographic procedure, an x-Ray beam is passed through the body. **A portion of the X-Rays are absorbed or scattered by the internal**

**structures and remaining x-ray pattern is transmitted to a detector** so that an image may be recorded for later evaluation.

- **Tomography:** It is any x-Ray technique in which shadows of superimposed structures are blurred out by moving x-Ray tube. Computational Tomography (also known as CAT Scanning), provides cross sectional imaging.

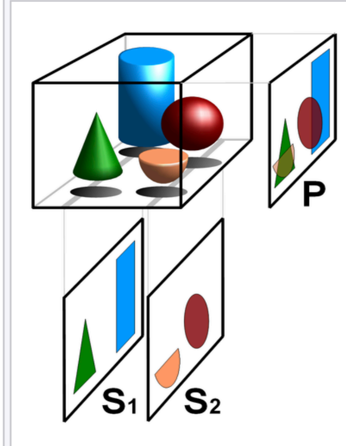



**Fig.1**: Basic principle of tomography: superposition free tomographic cross sections $S_1$ and $S_2$ compared with the (not tomographic) projected image P

- **Details of Computerized Tomography (CT) Scan**: It combines a series of X-Ray images taken from different angles around your body and uses computational processing to create a cross-sectional image (slices) of the bones, blood vessels, and soft tissues inside your body. **CT Scan can provide more detailed information than plain X-rays do**.

- **Applications**: CT scan has many applications, but it is particularly suitable for quickly examining people who may have internal injuries from car accidents or other types of traumas.

- **Risks**: During a CT scan **amount of radiation is greater** than what you would get during a plain X-ray because the CT scan gathers **more detailed information**. The low doses of radiation in CT-Scan have not been shown to cause long-term harm, although at higher doses, there may be a small increase in your potential risk of cancer.

## A) CT SCANS ASSOCIATED WITH INCREASED RISK OF BLOOD CANCERS (DEC 2023: SOURCE – TH)

- **Radiation doses** at moderate (over 100 mGy) to high (over 1 Gy) values are known to cause hematological malignancies (blood cancers) in both children and adults and other cancers. However, there is uncertainty about risk at low doses (less than 100 mGy) that are typically associated with diagnostic CT examinations. **A recent study published in *Nature Medicine, (Nov 2023) suggests that even low doses of radiation have a small probability to cause blood cancer***.

- **Analysis**: The results strengthened the body of evidence of increased cancer risk at low radiation doses and highlight the **need for continued justification of pediatric CT examinations and optimization of doses**.
- **Note:** gray (Gy) is the unit of ionizing radiation dose in the International System of Units (SI), defined as the absorption of one joule of radiation per Kg of matter. It **measures the energy deposited by ionizing radiation** in a unit mass of matter being irradiate and is used for measuring the delivered dose in radiotherapy, food irradiation, and radiation sterilization.

## 3. PYQS

| | |
|---|---|
| 1 | In which one of the following areas did the Indira Gandhi Centre for Atomic Research make significant progress in the year 2005? [Prelims 2006]<br>(a) Reprocessing the uranium-plutonium mixed carbide fuel of the Fast Breeder Test Reactor<br>(b) New applications of radioisotopes in metallurgy<br>(c) A new technology for the production of heavy water<br>(d) A new technology for high level nuclear waste management |
| 2 | In which one of the following locations is the ITER project to be built? [Prelims 2008]<br>A. Northern Spain<br>B. Southern France<br>C. Eastern Germany<br>D. Southern Italy |
| 3 | To meet its rapidly growing energy demand, some opine that India should pursue research and development on thorium as the future fuel of nuclear energy. In this context, what advantage does thorium has over Uranium? [Prelims 2012]<br>1. Thorium is far more abundant in nature than Uranium.<br>2. On the basis of per unit mass of mined mineral, thorium can generate more energy compared to natural Uranium.<br>3. Thorium produces less harmful waste compared to Uranium.<br><br>Which of the statements given above is/are correct?<br>A. 1 only<br>B. 2 and 3 only<br>C. 1 and 3 only<br>D. 1, 2 and 3 |
| 4 | India is an important member of the '**International Thermonuclear Reactor**'. If this experiment succeeds, what is the immediate advantage of India? [Prelims 2016]<br>A. It can use thorium in place of Uranium for power generation.<br>B. It can attain global role in satellite navigation.<br>C. It can drastically improve the efficiency of its fission reactors in power generation.<br>D. It can build fusion reactors for power generation. |
| 5 | In India, why are some of the nuclear reactors kept under "IAEA Safeguards" while other are not? [Prelims 2020]<br>(a) Some use uranium and others use thorium<br>(b) Some use imported uranium and others use domestic supplies<br>(c) Some are operated by foreign enterprises and others are operated by domestic enterprises<br>(d) Some are state owned, and others are privately owned |