5^{th} Semester B.E. Examination-Dec .2017/Jan. 2018
Introduction to Nuclear Power (15EE551)
Solutions

MODULE-1

1. a. **Define energy? What are different forms of Energy? Explain. (8 Marks)**

Ans:

- The concept of doing work to lift objects or to move an object such as a bicycle along can be called as energy. **Thus, it is relatively easy to understand the concept of energy as a measure of the ability to do work.**
- Energy can appear in different forms as follows:

  1. Kinetic Energy. This is energy associated with movement, for example, that of a flywheel or a moving locomotive.

  2. Potential Energy. This is energy possessed by virtue of position, typically in the earth's gravitational field. For instance, a child sitting on the higher end of a seesaw has greater potential energy than a child sitting on the lower end. Likewise, water in a mountain lake has greater potential energy than water at sea level.

  3. Chemical Energy. Matter consists of atoms that are combined together in molecules. Molecules of different substances can react to release energy and this releasable energy is often termed chemical energy. For example, chemical energy is released when gasoline combines with air in the cylinders of a car's engine.

  4. Electrical Energy. Atoms consist of a central mass, known as the nucleus, around which a cloud of electrons circulates. If there is an excess or deficit of electrons in one part of a body, the body is said to have an electrical charge and, by virtue of this, to have electrical energy. An example of this is a thunderstorm, where the clouds are charged electrically with respect to the ground.

  5. Nuclear Energy. Normally, the nucleus of an atom is stable and will remain indefinitely in its present state. An example is the nucleus of an atom of iron; no matter how much we would like it to happen, iron will never change into another element, such as gold. However, the atoms of some elements are unstable and can change into another form spontaneously, by the emission of radiation. It is sufficient here to note that the radiation emitted has kinetic energy and the disintegration process results in the release of energy associated with the nucleus, namely, the nuclear energy. If the nucleus could be weighed before the disintegration, and the resulting nucleus and all particulate components of the radiation weighed afterward, it would be observed that a small change in mass had occurred due to the conversion of mass into energy. The relationship between the loss of mass m and the energy released E is given by Einstein's famous equation:

  $$E=mc^2$$

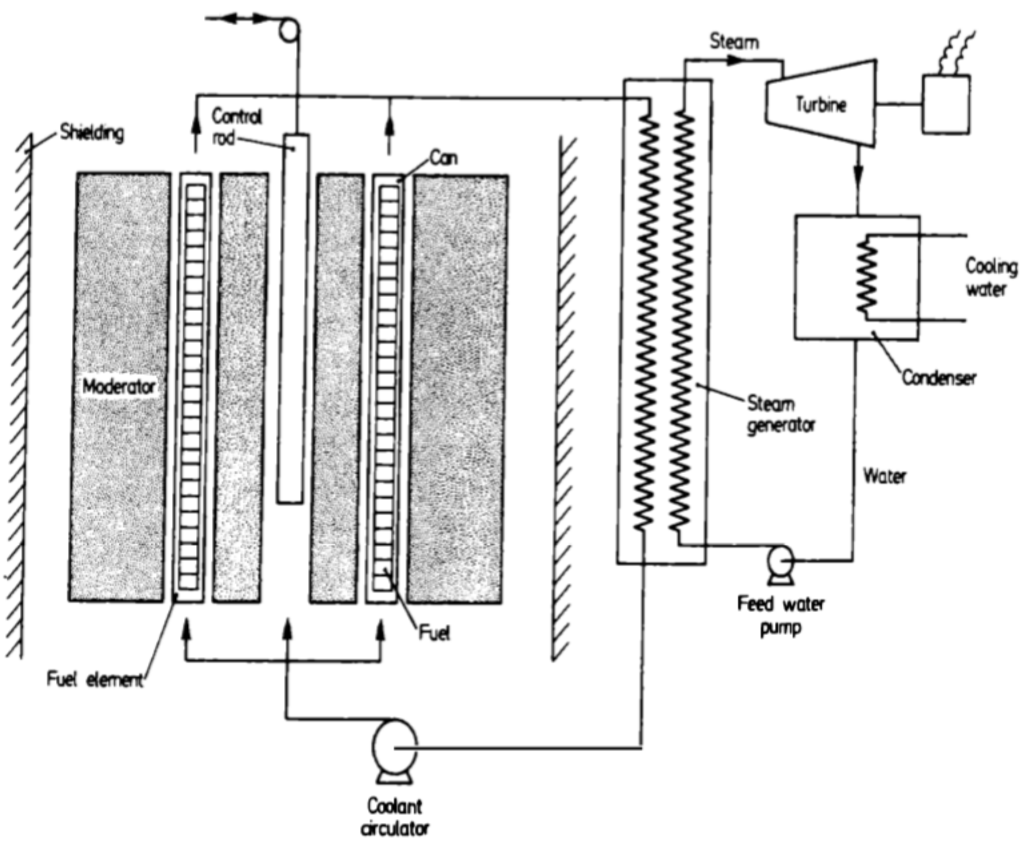
  Where 'c' is the velocity of light, 300,000 kilometers per second (186,000 miles per second). In a typical nuclear reaction, however, only a tiny fraction of the mass is converted into energy, typically 0-0. 1%. The disintegration of an unstable nucleus, and the consequent release of nuclear energy, can be stimulated by exciting the nucleus by bombarding it with radiation. This is at the heart of the fission reaction process, which we shall discuss further below. Nuclear energy can also be released, as we shall see, by the fusion of very light atoms into heavier ones.

  6 Thermal Energy. The atoms of all substances are in constant motion. In a solid the atoms are held in an approximately fixed position with respect to one another. However, they all vibrate to an extent that increases with increasing temperature. The energy associated with this vibration is called thermal energy. In fluids (namely, liquids and gases), two or more atoms may be combined with each other chemically in the form of molecules. These molecules have vibrational energy, but in the fluid state they may also have translational energy arising from their motion in space and rotational energy arising from their rotation. All of these components of energy add up to the thermal energy of the fluid. It will be seen from this description that thermal energy is of a special type. It is associated with atomic or molecular movements that are randomly directed. This makes it very much more difficult to convert thermal energy into other forms of energy, as we shall see below.

b. With neat diagrams explain basic components of nuclear reactor. (08 Marks)

Ans:

Basic Components of Nuclear Reactor:



1. Fuel
Generally Uranium-235 is used as the basic fuel. The uranium oxide (UO2) pallets are arranged in tubes which work as fuel rods. The rods are further arranged into fuel assemblies in the reactor core.
2. Moderator
This is core material which uses to slow down the speed of released neutrons that can be undergo other fission. Usually water or heavy water or graphite is used for this purpose.
3. Control Rods
They work as a controller to control the rate of nuclear reaction to avoid the nuclear explosion. These rods are made with neutron-absorbing material like cadmium, hafnium or boron etc. They can be inserted or withdrawn from the core according to the requirement for control or speed up the rate of reaction respectively.
4. Coolant
Generally water is used as coolant. This is a liquid or gas that circulates from the core to transfer the heat from it.

5. Pressure Vessel or Tubes
This is a robust steel vessel that contains the reactor core and moderator or coolant. If the tubes are used then these are series of tubes that holds the fuel.

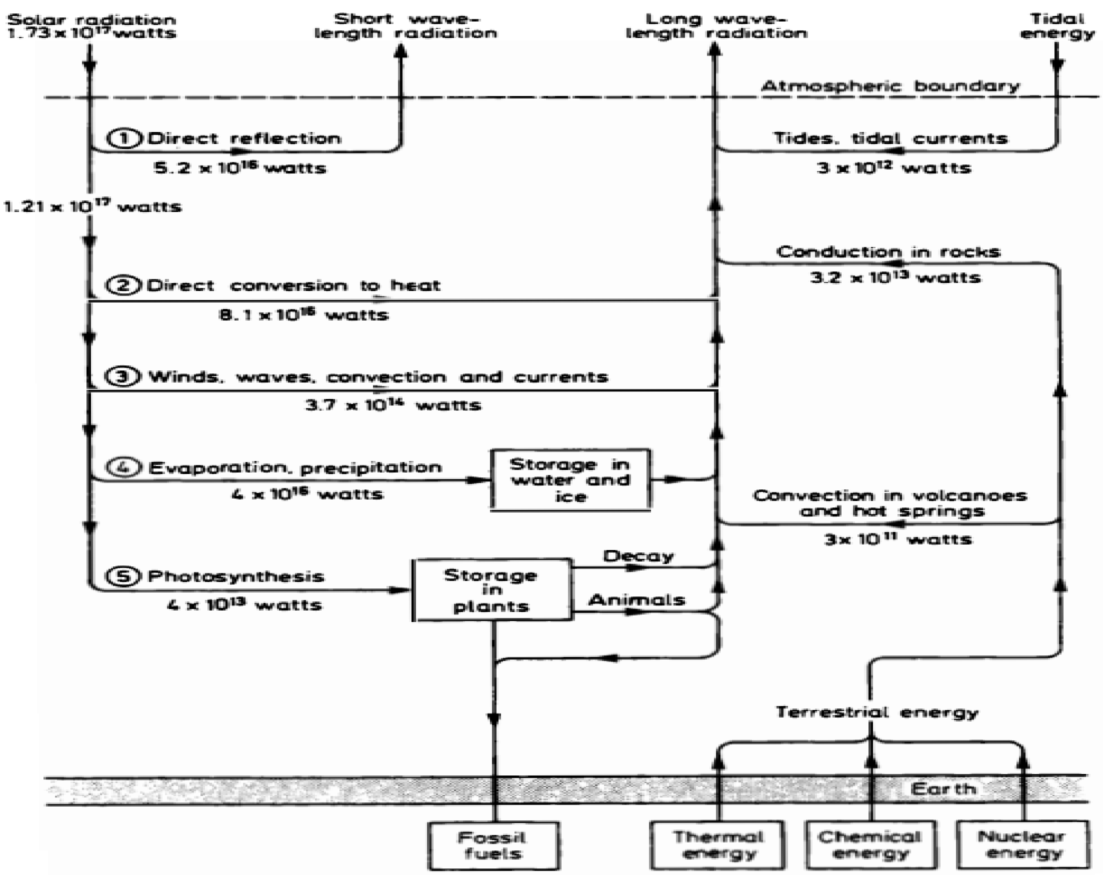
6. Steam Generator
The steam generator is the part of the cooling system. In the steam generator, the heat from the reactor comes from the primary coolant and this heat is used to make steam for the
turbine.

7. Containment
The containment works to protect the reactor form outside intrusion and the effects of radiation. This is a meter thick concrete and steel structure around the reactor core.

OR

2. a. Draw the energy flow diagram for earth. (6 Marks)

Ans:



Energy flow diagram for the earth. From Dorf (1978).

b. Explain working of fast reactors. (6 marks)

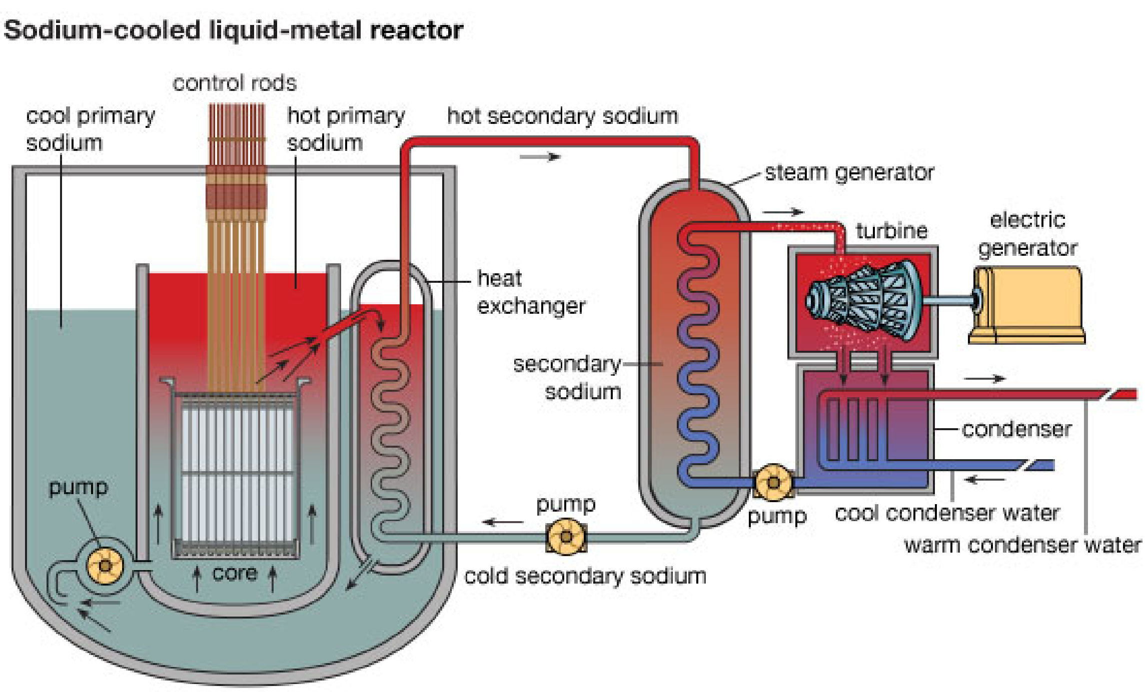
Ans:

- A fast-neutron reactor or simply a fast reactor in which the fission chain reaction is sustained by fast neutrons

- Such a reactor needs no neutron moderator, but must use fuel that is relatively rich in fissile material when compared to that required for a thermal reactor.

Liquid Metal-Cooled Fast Breeder Reactors:

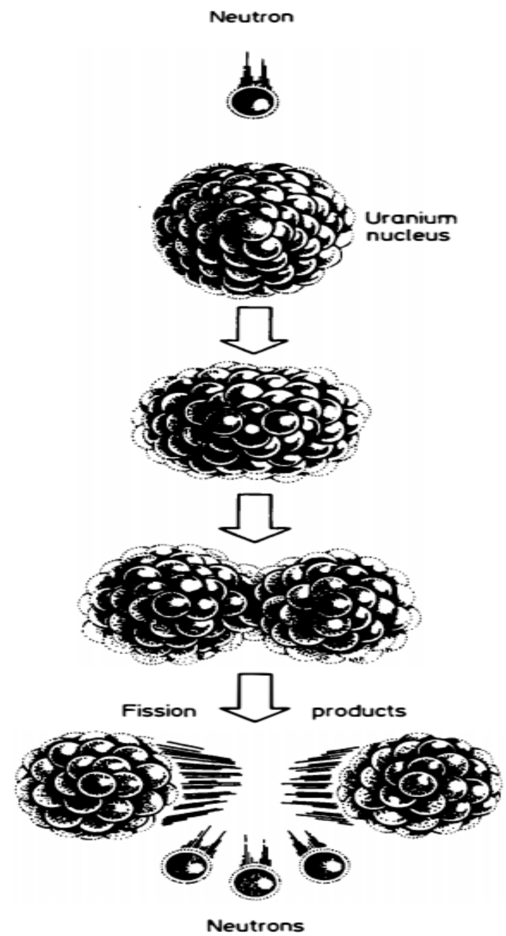
- Most prevalent design is employing sodium as the coolant
- sodium is excellent heat transfer agent and can cope with the very high volumetric power densities encountered in reactors
- consists of a pool of sodium in a primary vessel in which the core is submerged
- Sodium is pumped through the core
- The hot sodium passes through intermediate heat exchanger, where heat is transferred from the primary coolant to a secondary sodium stream
- the secondary stream passes through the steam generator, where steam is raised for electricity generation
- this reactor has three heat transfer stages
  1. from the fuel elements to the primary sodium coolant
  2. between the primary sodium coolant and a secondary coolant
  3. between this secondary coolant and evaporating water in the steam generator
- complex system ensures the primary coolant stays in the primary vessel and any radioactive substances in the primary vessel are not transferred to the steam generator(to avoid chemical interaction between sodium and water)



c. Explain the Fission Process. (4 Marks)

Ans:

- Rapid release of Energy is possible in nuclear fission.
- Neutron from a decay process collide with a heavy nucleus & splits it into small nuclei(fission product) while releasing energy & some more Neutrons.
- This chain reaction of Fission is self sustaining if more mass is present.



Diagrammatic view of fission process.

$$^{235}U + n \longrightarrow {}^{141}Ba + {}^{92}Kr + 3n \longrightarrow \text{Fission}$$

Equation

(Uranium)

- Release of Energy in the Fission process can be discussed as per the equation where ^{235}U splits into Barium & Krypton atoms , where as 3 neutrons are released.
- Mass of Right hand side in the equation is 0.091% less than that of the left hand side i.e. approximately 0.1% of original mass is actually converted into energy.
- This Energy appears as Kinetic Energy of Fission Product & neutrons, which then collide with surrounding atoms & increases thermal vibration(Releases Heat).
- For each Kg of ^{235}U fissioned by above reaction 80million million ($8x10^{13}$) Joules are released. (Equivalent to energy of 3000tons of coal.)

MODULE-2

3. a. What are general features of Reactor Coolant? Explain. (8 Marks)

Ans:

GENERAL FEATURES OF A REACTOR COOLANT:

- **High specific heat:**

✓ The **specific heat** is the amount of heat required to heat 1 kg of a substance by 1 K (1 °C) and thus has the units joules per kilogram per kelvin.

✓ $Q=MCp\Delta T$ => Cp- Specific heat, Q- Heat flow

✓ ΔT= Tout-Tin, $\Delta T \alpha 1/Cp$

✓ It is important to prevent excessive temperatures within the core, to avoid damage of fuel and core materials.

✓ a fluid can be chosen with a high value of CP which will limit the outlet temperature.

✓ Latent Heat is important in Boiling liquid coolant as excess heat is used to change state without changing Temp.

✓ Latent Heat of vaporization- Heat required to change 1kg of liquid to gas

✓ $Q= MLv$ Lv- Latent Heat

- **High rates of heat transfer:**

✓ Rate at which Heat transfers from Fuel to Coolant

✓ Depends upon Thermal Conductivity

✓ Liquid Metals have high value & Gaseous Coolants have low value

- **Good nuclear properties :**

✓ Should have low neutron absorption

✓ Shouldn't be reactive otherwise isotopes are created

✓ If coolant is moderator then good moderation properties required

✓ In fast reactors Coolant shouldn't be moderator as it will reduce speed

- **Well-defined phase state:**

✓ Same phase should be maintained

✓ BP should be high for this in liquids

- **Cost and availability:**

✓ Minimum Cost

✓ Coolant should be freely available

- **Compatibility:**

✓ Coolant shouldn't corrode the reactor

- **Ease of pumping:**

- ✓ If viscosity is low, requires less pumping

✓ The viscosity of a fluid is related to its temperature, that of liquids decreasing with increasing temperature and that of gases increasing with increasing temperature.

✓ The viscosity of a fluid is indicated by the symbol μ

Figure of merit (F):

- ✓ It is Related to Heat transfer & Pumping

$$F = \frac{C_p^{2.8} \varrho^2}{\mu^{0.2}}$$

- ✓ Cp is the specific heat
- ✓ e is the fluid density (kilograms per cubic meter)
- ✓ μ is the viscosity

b. Describe operational states that can occur during normal operation of a reactor. (8 Marks)

Ans:

Reactor operational states:

1. **Normal Operation & Operational Transients:**

✓ In addition to the normal operational state designer must think about transients that occur during operation. The term transient implies a nonsteady state of operation encountered in proceeding normally from one steady operating state to another.

✓ An example would be bringing the reactor from a "cold" condition up to full power operation.

✓ There may be limits to the rate at which the temperature of the structure can be increased or decreased

✓ In order to operate the reactor economically, consideration must be given not only to the steady state but also to all the things that are likely to happen as a matter of course in the operation of a complex engineering plant

2. **Upset Conditions:**
   - ✓ Upset is used to describe all the kinds of faults that are not expected during operation but that can be reasonably expected to occur during the lifetime of a plant as a result of a variety of external events.
   - ✓ For example, the case of lightning striking the power lines leaving the plant
   - ✓ The action is to stop the flow of steam to the turbine and divert it directly into the condenser.
   - ✓ The steam flow is reduced as rapidly as possible by using the control rods to stop the fission reaction-"tripping" the reactor. A turbine trip of this kind might be expected to occur for one reason or another.
   - ✓ The power station, instead of being an exporter of electricity, immediately becomes an imporer of electricity in order to drive the coolant pumps, instrumentation, and emergency cooling systems for the reactor

3. **Emergency events:**

✓ A number of events can be postulated that might have, say, a 1-in-10 chance of occurring in the lifetime of a particular plant

✓ The reactor design must cope with such emergencies, although some damage to plant components may b expected as a result of the incidents.

- ✓ An emergency event may occur, as a result of breaks in small pipes in the reactor circuits, relief valves being stuck open, or fires within the plant electrical systems.

4. **Limiting fault condition:**

- ✓ It is possible that due to some events, such as an earthquake, the complete severance of a main inlet pipe, or the complete severance of a steam line from the steam generator to the turbine occur, that represents a severe accident to a reactor.
- ✓ Even though some accidents might occur only once in 10,000 years of reactor operation (though with 100 reactors operating, such an event might occur once every 100 years), reactors must be designed to meet these so-called limiting fault conditions safely.
- ✓ Although an emergency event (as described above) would not give rise to any release of activity off the reactor site, a limiting fault condition could give rise to extensive failure of the fuel canning and some consequent release of radioactivity off the site.

Classification of Reactor Operating States and Frequency of Occurrence

Operating states for which the system is designed to cope:	
Normal operation	Continuous (apart from shutdowns for maintenance)
Operational transients	~10 per reactor year
Upsets	~1 per reactor year
Emergencies	1 in 100 reactor years
Limiting fault conditions (including design basis accident, DBA)	1 in 10,000 reactor years
Unprotected or beyond design basis accidents	1 in 1 million reactor years

- The reactor must be designed to meet the above operating states.
- Certain faults-for example, those related to coolant circulation pumps or gas circulators-can give rise to an interruption in normal cooling.
- When such an interruption occurs, the reactor is shut down by its automatic safety systems.
- But as we saw earlier, heat generation continues after shutdown of the fission reaction due to the continuing decay of the fission products that have been generated: the decay heat.
- So all reactor systems are provided with alternative means of cooling in order to remove this decay heat in the event that the normal cooling system fails
- The two most important safety systems are those **1. Associated with stopping ("tripping") the fission reaction within the reactor (the control rods) and 2. Those associated with providing an alternative cooling system, the so-called Emergency Core Cooling System (ECCS).**
- These ***engineered safety*** systems need to be brought into operation reliably when required.
- This is done as a result of instrumentation signals received from sensors located around the plant that indicate when an unsatisfactory condition is being approached. They then initiate the action of the safety systems.

- This total reactor protection system has to be highly reliable. Such reliability is achieved through:

1. Duplication:

✓ Several sensors are used to measure critical parameters and several signal processors used to evaluate the signals. If all the sensors and processors are working, some of them are redundant.

✓ If there are four identical sensors whose readings are compared & two sensors of the four give identical signals requiring the activation of the safety system, action is taken.

2. Diversity:

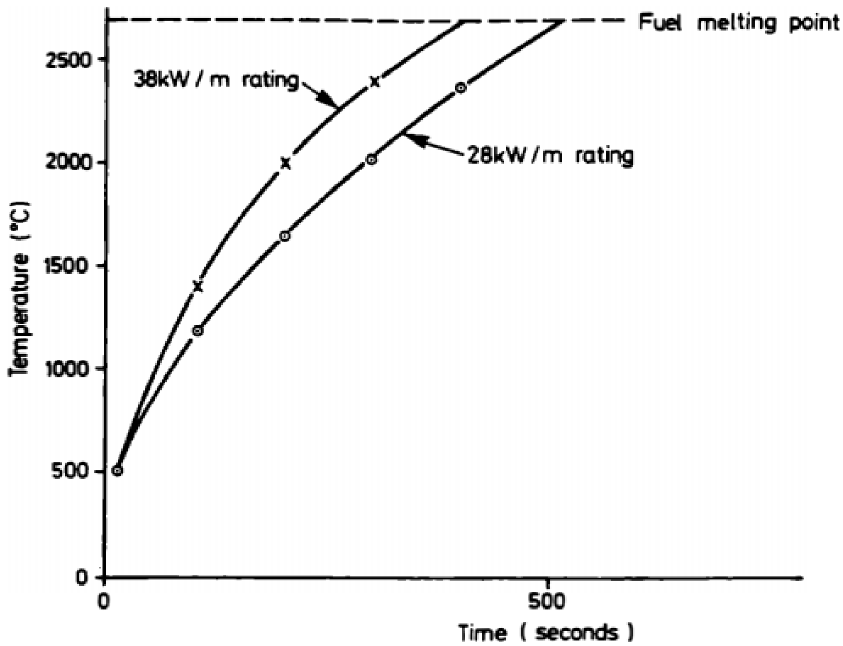
✓ Different systems parameters are monitored to provide an indication of the same form of fault condition.

✓ Thus, two completely different signals, e.g., pressure and temperature, can be used to trip the reactor and/or initiate the Emergency Core Cooling System (ECCS) for the same fault.

- In some designs-for example, the British PW the reactor protection system itself consists of two diverse systems: **1. The primary protection system 2. The secondary protection system**.
- The primary protection system is a microprocessor-based system that provides reactor trip and actuation of the engineered safety systems.
- The secondary protection system utilizes magnetic logic relays to initiate the reactor trip and engineered safety systems independent of the prior protection system
- Physical trip systems in Advanced Gas-Cooled Reactors (AGR) have two separate systems for terminating the fission reaction: **1. based on the control rods 2. By the injection of nitrogen into the reactor gas which is a neutron absorber.**
- **Pressurized Water Reactors (PWRs) will shut down automatically** if cooling water is lost from the core since this water is also the moderator.
- Operational transients, upsets, emergency events, and limiting fault-conditions, as defined above, represent the range of conditions against which the plant is designed.
- The most serious of these conditions, the limiting fault condition, is often referred to as the **Design Basis Accident (DBA).**
- Already we have discussed the basic principles of controlling the nuclear reaction and cooling the fuel, we need to introduce a third basic principle, that of containing the radioactivity. Collectively these three basic principles of reactor safety can be remembered as the 3 Cs .
- Basic principles related to the energy aspects of an accident is simple energy balance for the reactor system:

  Energy in-Energy out= Energy Stored
- Any transient process causing a departure from steady state conditions will also cause a change in the stored energy.
- The concept of the energy balances associated with transient conditions can also be applied to the case of heat release via breaks in the reactor circuit. These will lead to a loss of primary circuit coolant, reducing the amount (or inventor) of this coolant in the circuit.
- If the coolant is released from the circuit in the form of a vapor, it takes with it much more energy than if it is released in the form of a liquid, and this is advantageous in reducing the energy storage (e.g., the amount of heat stored in the fuel elements) during the transient situation.
- A very extreme case of heat retention in the fuel is that where no heat at all is removed from the fuel following a transient leading to a reactor trip.
- Initially, the fuel temperature becomes equalized, which gives rise to an initial relatively rapid increase in the fuel surface temperature.

- The fuel element continues to heat up because of heat released during fission product decay, and this rate decreases with time as the fission products gradually disappear
- Fuel will ultimately reach its melting point, however, and in designing for the various levels of transient condition it is obviously important to prevent this from occurring.
- The rate of rise of temperature of the fuel will depend on the initial heat rating, which determines the amount of fission products present at any given time.



Adiabatic heat-up for PWR fuel

OR

4. a. List the advantages & disadvantages of boiling coolants. (5 Marks)

Ans:

- **Advantages:**

➢ Vapour produced is directly fed to Turbine

➢ Good Heat Transfer capacity

➢ Evaporation produces mix of Vapour & liquid: so low neutron absorption & high Heat Transfer

➢ Proportion of Vapour in Coolant is Void Fraction. As Void Fraction increases neutron absorption decreases & reactivity increases. There are 2 cases:

❖ If Boiling liquid is moderator , then Neutron population decrease with increase in void fraction

❖ If separate moderator is used then reactivity & neutron population increase with increase in void fraction

- **Disadvantages:**

➢ Due to dry out efficient boiling can become inefficient vapour cooling

- Power generation circuit becomes radioactive as the vapour directly comes from the core, so maintenance needed & cost increases
- Complex behaviour to void coefficient

- **Water:**

- ✓ Used in BWR
- ✓ Liquid & boiling water features are almost same
- ✓ BWRs operate at low pressure
- ✓ Water can decompose into H & O while boiling, it is dangerous
- ✓ Stress Corrosion Cracking may occur

- **Liquid Metals:**

- ✓ Boiling Potassium is used for terrestrial & space power system reactors
- ✓ High Thermodynamic efficiency
- ✓ Exotic materials required for Cladding & turbine design, so less used

b. Describe various operating states for sodium cooled fast reactor. (6 marks)

Ans:

- The various operational states for a liquid metal-cooled fast reactor (LMFBR) can be listed as follows:
- **Normal operation and operational transients.**
  - ✓ The sodium in the circuit is always kept in a molten state by heating the whole circuit with electrical resistance heaters wound on all the pipework.
  - ✓ This maintains the sodium at a temperature of at least 100°C (the melting point of sodium is 98°C). The large pool of molten sodium responds rather slowly to heat input.
  - ✓ Thus, the coolant takes some time to reach operating temperature.
- **Upsets.** Various categories of upset situations have been postulated like loss of load, turbine trip, loss of feedwater, and loss of a single main circulating pump.
- **Emergency conditions.** Emergency conditions will occur if the upsets described above cannot be contained within normal operational procedure.

1. **Loss of electric power to the primary coolant pumps** causes them to coast down to zero speed. Under these circumstances, the reactor is immediately tripped and power may be reinstated to the circulators from emergency supplies.
   - ✓ However, the sodium pool itself represents a major heat sink. For instance, with the decay heat in the reactor alone, the sodium pool would take about 24 h to reach the boiling point if there were no heat removal at all.
   - ✓ Moreover, the reactor has decay heat removal heat exchangers that are connected to the primary circuit and can remove the decay heat by natural circulation alone, without any electric power input to the reactor.
   - ✓ The final heat sink from these removal systems is the atmosphere via air-cooled heat exchangers.

2. **Inadvertent increase in neutron population** in the core by inadvertent removal of a control rod, movements of the fuel or sodium boiling in the core so the rate of the fission reaction can be increased.
   - ✓ Sodium boiling in the inner region of the core causes an increase in the rate of fission (neutron population), since sodium absorbs neutrons, and if it is partially vaporized, the absorption is reduced.
   - ✓ However, if the boiling occurs in the outer region of the core, the reduced local density causes increased leakage of neutrons from the core and gives rise to a reduction in the fission reaction (neutron population).
   - ✓ Thus, the effect of sodium boiling is usually negative for small reactors and positive for larger reactors, where any boiling is likely to be away from the boundary of the core.
3. **Local damage within a fuel subassembly.**
   - ✓ The reactor core consists of hundreds of separate groups of fuel elements, which can be inserted or removed independently from the core.
   - ✓ Attention has been focused on the possibility of blockages occurring within individual subassemblies or groups of subassemblies.
   - ✓ If the sodium flow is blocked, local melting of the cladding and possibly the oxide fuel could occur & the oxide fuel reacts with the sodium, limiting its useful lifetime.
   - ✓ But the failure of a subassembly can usually be detected by specially provided instrumentation.
   - ✓ Failure to detect the fault may lead to escalation of the upset into a fault condition.
4. **Loss of heat removal from secondary sodium or steam systems.**
   - ✓ Here the system responds in the manner described for the loss-of-flow upset.
   - ✓ The reactor is tripped and natural circulation cooling is set up, with heat released by the decay heat removal heat exchangers.
   - ✓ The circulators may still operate under these circumstances.

- In response to the various operating states, it can be cooled by either (1) **primary circuit cooling by the intermediate sodium circuit to the steam generators** or (2) **primary circuit cooling via the separate liquid metal coolant circuit to air-cooled heat exchangers**.
- In the first case, the primary circuit uses forced circulation, while the secondary intermediate circuit can rely on natural convection.
- In the 2nd case, natural circulation in the primary circuit is sufficient to cool the core, and indeed if all the heat exchangers are operational, natural convection is sufficient in the secondary circuit.
- However, if this is not the case, a powered fan is necessary to force air across the heat exchanger.

c. List the problems associated with using light water as a coolant. (5 marks)

Ans:

- ✓ Low BP, so high Pressure required
- ✓ In neutron flux it decomposes to H & O
- ✓ Hydrogen is explosive
- ✓ It is corrosive
- ✓ Strong absorber of Neutron so 2 problems arise

1. Enriched Fuel required
2. When Coolant removed Neutron concentration increase & Rate of reaction also increase

MODULE-3

5. a. Discuss Browns Ferry fire accident. What are the lessons learnt from this incident? (8 Marks)

Ans:

- The Browns Ferry nuclear power plant in Aabama consists of three 1065- MW(e) boiling-water reactors.
- On March 22, 1975, a workman who was lying on his side used a lighted candle to test for leakage of air around cable penetrations through a concrete wall at the Unit I plant.
- A hole was found, and the workmen stuffed some polyurethane sheet into it and tested again for leaks.
- The leak persisted, and the candle flame ignited the polyurethane sheet.
- The air rushing into the hole spread the fire into the hole and away from the workmen so that they could not extinguish it with fire extinguishers.
- The fire burned for 7 h before it was put out. Units I and 2 were both at full power when the fire started.
- The fire spread horizontally and vertically, affected about 2000 cables, and caused damage that cost about $10 million to repair.
- There was a reluctance to use water on the fire until both reactors were in a stable shutdown condition because of the possibility of short -circuiting.
- Once water was used, the fire was rapidly put out.
- Both reactors were shut down. However, because of the fire, both the shutdown cooling system and the emergency core cooling system for Unit 1 were inoperable for several hours.
- The operators had to use alternative means of injecting water into the reactor, which included a pump used in connection with the control rod drive system and pumps used for returning condensate to the system.
- The use of these alternative water supplies required depressurization of the reactor, and during this maneuver, the water level over the core dropped to 1 .2 m above the top of the fuel.
- However, sufficient cooling was provided throughout the incident to prevent the core from overheating.
- No significant problems were encountered with the cooling of Unit 2, and the high-pressure cooling system (HPIS) was successfully initiated.
- **The main lesson from the Browns Feny incident was related to what is called common mode failure.**
- All the cables related to the safety systems passed through a single duct and failed in a common mode and all the systems failed when there was a fire.
- So the designer should ensure that each of the independent systems is truly independent and that supplies and controls to the instrumentation and actuation devices should not pass along common ductwork.
- The technical term for this is **segregation**, and after the Browns Feny incident the provisions for segregation were significantly improved.

b. What are the designs short coming of Chernobyl reactor explain. (8 Marks)

Ans:

Design Shortcomings:

- ✓ First, the concept and design of the reactor itself was the major contributory factor.
- ✓ While the RBMK reactor has some inherent features that made it quite attractive (including the lack of a thick-walled pressure vessel, the absence of steam generators, the capability to replace fuel on load, and ease of construction on remote sites), it also has features that were shortcomings:

1 . Positive power co-efficient at low power levels:

The power coefficient and design of a reactor dictates its behavior and stability. If the power coefficient is negative, any power rise will be self-limiting; if positive, the converse. The power coefficient is made up of a number of individual components, but in the case of the RBMK, two components are dominant: the negative effect of fuel temperature (Doppler) increases and the positive effect of an increase of steam voidage in the core. At power levels below 20%, the positive void coefficient becomes much stronger than the negative fuel temperature coefficient. As a result the power coefficient is overall positive and the reactor unstable.

2. Slow shutdown system.

The reactor control and protection system was too slow and inadequate in design. The shutdown system was dependent for its effectiveness on appropriate operation of the reactor control system, which was complex and largely manual. Because computers were rudimentary and unreliable when the RBMK reactor was originally conceived, the designers assumed that human operators would be more reliable. They failed to see the need for engineered safeguard features to counteract the operator's driving the reactor into extreme situations for which the slow shutdown system would be ineffective.

3. "Positive scram. "

Associated with the poor design of the protection system is the design feature that with the control rods fully withdrawn, the initial effect of insertion is to increase reactivity in the lower parts of the core, due to the displacement of water by the graphite followers. Normally, the entry of the boron carbide absorbers would reduce reactivity at the top of the core and overwhelm this increase. However, in the specific sequence of April 26, 1986, because of the double-peaked axial flux profile resulting from the xenon transient, this was not the case. The converse happened: entry of the control rods initially produced either a neutral or even a slight increase in reactivity-"positive scram."

4. Design of containment. This was inadequate to cope with this extreme accident. The RBMK reactors do not have a common containment to cover both the reactor and primary circuit.

OR

6. a. Explain NRx incident. What is lesson learnt from this incident. (8 Marks)

Ans:

- The NRX reactor in Chalk River, Canada, is an experimental reactor.
- It was designed to operate at a full power of 40 MW(t).
- Single fuel rods are cooled by light water flowing in an annulus between the rod and a pressure tube, which in turn passes through a calandria tube mounted in a tank of heavy water, which acts as the moderator.
- On December 12, 1952 the reactor was undergoing tests at low power.
- Several red lights indicating withdrawn control rod positions suddenly came on, the supervisor went to the basement and found that an operator was opening valves that caused the control rod banks to rise to their fully withdrawn positions.
- He immediately closed all of the incorrectly opened valves, after which the rods should have dropped back in.
- Some of them did, but for unexplained reasons, others dropped in only enough to cause the red lights to turns off which were almost completely withdrawn.
- The supervisor phoned his assistant in the control room, intending to tell him to start the test over again and to insert all the control rods.
- Operator in the control room soon realized that the reactor power was rising rapidly and he pressed the "scram" button to trip the reactor.

- The control rods should then have dropped in under the action of gravity, but many of them did not, and the power continued to climb.
- It was decided to dump the heavy-water moderator from the calandria tank; this shut down the reactor, but not very quickly since it took some time to drain. The reactor power had peaked between 60 and 90 MW(t).
- The increase in power caused boiling of the light water, which increased the internal pressure and caused the coolant pipes to rupture.
- The situation was exacerbated by the fact that loss of the light water from the fuel channels gave an increase in reactivity and increased the initial power pulse.
- Some fuel melting was experienced, and the heavy-water calandria tank was punctured in several places.
- The main lesson learned from this incident was that absolute security of control rod operations is mandatory, and modern system goes to great lengths to achieve this.
- This kind of system has a positive void coefficient, so boiling of the water due to heat leads to an increase in neutron population.

b. List the safety measures taken to improve the safety characteristics of RBMK reactor at Chernobyl. (4 Marks)

Ans:

- Russia and Ukraine have now implemented a number of measures to improve the safety characteristics of the RBMK reactors.

1. The control rod positional set points have also been reset so that all the control rods "dip" into the core at least 1.2 m, with the physical capability to prevent their being withdrawn outside that limit.

2. The minimum number of control rods in the reactor at any one time has been doubled to 70.

3. Void coefficient has been significantly reduced so that the reactor cannot become prompt-critical. This has been done by increasing the number of fixed absorbers in the core. To compensate for the associated loss of activity, the fuel enrichment has been increased from 2% to 2.4% U-235.

4. Additional instrumentation has been provided to measure subcooling at the inlet to the main circulating pumps.

5. Additional independent "fast" shutdown system with an insertion time of 1-2 seconds has been introduced.

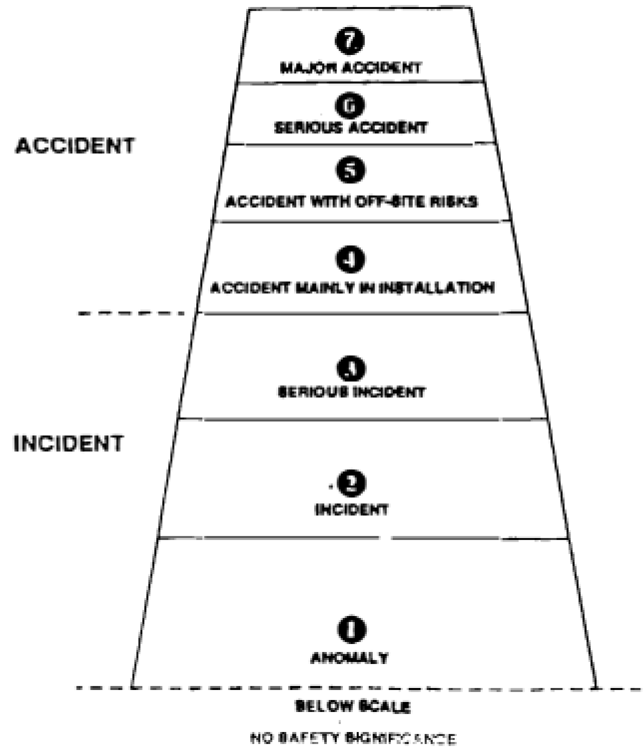
c. Discuss the International Atomic Energy Agency Scale for events at nuclear installation. (4 Marks)

Ans:

- ✓ In 1990 the International Atomic Energy Agency (IAEA) introduced a seven level scale designed to allow prompt classification of such events.
- ✓ Three criteria are applied:
  1. Levels 3-7 relate to the extent of releases of radioactivity off-site.
  2. Levels 2-5 relate to the extent of on-site contamination or exposure.
  3. Levels 1-3 relate to the extent to which the defense-in-depth philosophy has been challenged

The International Nuclear Event Scale

For prompt communication of safety significance



Level	Descriptor	Criteria	Examples
Accidents			
7	Major accident	• External release of a large fraction of the reactor core inventory typically involving a mixture of short- and long-lived radioactive fission products (in quantities radiologically equivalent to more than tens of thousands terabecquerels of iodine-131).	Chernobyl, USSR 1986
		• Possibility of acute health effects. Delayed health effects over a wide area, possibly involving more than one country. Long-term environmental consequences.	
6	Serious accident	• External release of fission products (in quantities radiologically equivalent to the order of thousands to tens of thousands of terabecquerels of iodine-131). Full implementation of local emergency plans most likely needed to limit serious health effects.	
5	Accident with off-site risks	• External release of fission products (in quantities radiologically equivalent to the order of hundreds to thousands of terabecquerels of iodine-131). Partial implementation of emergency plans (e.g., local sheltering and/or evacuation) required in some cases to lessen the likelihood of health effects.	Windscale, UK 1957
		• Severe damage to large fraction of the core due to mechanical effects and/or melting.	Three Mile Island, USA 1979
4	Accident mainly in installation	• External release of radioactivity resulting in a dose to the most exposed individual off-site of the order of a few millisieverts.[a] Need for off-site protective actions generally unlikelyexcept possibly for local food control.	
		• Some damage to reactor core due to mechanical effects and/or melting.	Saint Laurent, France 1980
		• Worker doses that can lead to acute health effects (of the order of 1 Sievert).[b]	
Incidents			
3	Serious incident	• External release of radioactivity above authorized limits, resulting in a dose to the most exposed individual off-site of the order of tenths of a millisievert.[a] Off-site protective measures not needed.	
		• High radiation levels and/or contamination on-site due to equipment failures or operational incidents. Overexposure of workers (individual doses exceeding 50 millisieverts).[b]	

		• Incidents in which a further failure of safety systems could lead to accident conditions, or a situation in which safety systems would be unable to prevent an accident if certain initiators were to occur.	Vandellos, Spain 1989
2	Incident	• Technical incidents or anomalies which, although not directly or immediately affecting plant safety, are liable to lead to subsequent reevaluation of safety provisions.	
1	Anomaly	• Functional or operational anomalies which do not pose a risk but which indicate a lack of safety provisions. This may be due to equipment failure, human error, or procedural inadequacies. (Such anomalies should be distinguished from situations where operational limits and conditions are not exceeded and which are properly managed in accordance with adequate procedures. These are typically "below scale.")	
Below scale /	No safety significance		

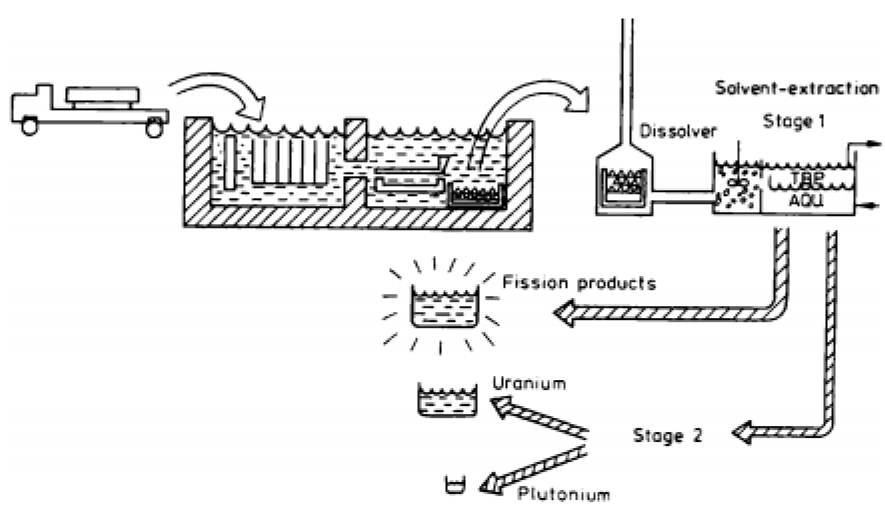
MODULE-4

7. a. Discuss the valuable materials that can be present in the fuel removed from plant. (6 marks)

Ans:

- The fuel removed from a nuclear reactor contains three kinds of valuable material:
  1. The **unused proportion of the fissile material** that was originally introduced with the fresh fuel.
  2. **New fissile material** that has been bred as a **result of the nuclear reactions** between neutrons and ^{238}U to form ^{239}Pu. The plutonium produced can be used as a fissile material in both thermal and fast reactors.
  3. Much of the **original ^{238}U**, the **nonfissile isotope** of uranium, still remains which can be converted to ^{239}Pu.
  4. If it has been decided to reprocess spent fuel with the objective of recovering valuable uranium and plutonium, the fuel must first be transported to a reprocessing plant using the flasks described in the previous section.
- In a modern reprocessing plant like THOR (Thermal Oide Reprocessing Rant) operated by British Nuclear Fuels at Sellafield, the actual separation process is undertaken after at least 5 years' storage of the spent fuel in the ponds.
- The fuel element is first stripped of as much of its extraneous metal structure (grids, support plates, etc.) as possible.
- These remnants are stored separately and treated as **intermediate-level waste**.
- The fuel pinsthemselves are sheared into small lengths between 1 and 4 in. ; these sheared fuel pieces fall down a chute into a perforated basket.
- This basket is then transferred to the **dissolver**.
- The shear needs to be of modular construction to allow replacement of the blade and for maintenance.
- In the dissolver the fuel is dissolved in hot (90°C) 7M Nitric acid.
- The cladding pieces, or "**hulls**," are withdrawn in the basket and again sent for disposal as **intermediate-level radioactive waste.**
- As the fuel dissolves, fission gases are released: **the inert gases krypton and xenon and other volatiles such as iodine and carbon dioxide as well as oxides of nitrogen and steam**.

- The fuel solution itself still contains some undissolved particulates, both from the cladding and from fission products. The solution is therefore clarified using a centrifuge.
- The clarified Nitric acid solution containing the fission products, the uranium, and the plutonium is next passed through the chemical separation plant.
- This involves a solvent extraction system. Solvent extraction is a process that allows separation of dissolved materials.
- Reprocessing plants use mechanical stirrers to mix the two liquids, followed by settling tanks that allow their separation, with each of the liquids containing the respective components. These are called **mixer settlers.**
- Vertical pipes containing perforated metal plates may be used, with one fluid flowing up the pipe and the other flowing down it.
- To promote mixing of the fluids, such columns are subjected to pulses, and they are often referred to as **pulsed columns.**
- The first objective of solvent extraction in the reprocessing plant is the separation of the valuable uranium-plutonium mixture from the nitric acid solution.
- This is done by contacting the nitric acid fuel solution with an organic solvent, typically tributyl phosphate (TBP) diluted with odorless kerosene (OK).
- Separation of the uranium from the plutonium is also achieved by solvent extraction.
- The first step is to redissolve the mixture in a clean acid stream and then add a substance to the stream to change the condition of the plutonium and render it insoluble in TBP.
- The final stage of the extraction is to take the uranium from the TBP stream by contacting the stream again with an aqueous phase having a low concentration of nitric acid.
- The output of the separation stages in the reprocessing plant consists of streams of uranium, plutonium, and fission products dissolved in nitric acid.
- The uranium and plutonium are precipitated as uranium and plutonium nitrates, & then heated to be converted into oxides, so that it can be reused in the preparation of nuclear fuel.
- The thermal and radiation problems in reprocessing plants are obviously fewer the longer the fuel has been stored in the cooling ponds prior to reprocessing.
- Fast reactors present greater difficulties for reprocessing than thermal reactors.
- They already have a higher specific heat generation rate, and their spent fuel must be reprocessed on a much shorter time scale, typically 69 months after removal from the reactor.



Schematic diagram of reprocessing plant.

b. Explain the reasons for failure of reactor vessel. (7 marks)

- The reactor pressure vessel represents the second containment barrier or line of defense which consists of a massively thick ferritic steel structure.
- The vessel might fail due to:
  1. gross overpressurization
  2. displacement or damage from the support structures
  3. creep failure due to overheating or vessel wall thinning
  4. shock loadings due to internal fuel-coolant interactions or hydrogen
  5. explosions
- Over pressurization could occur as a result of the reactors failing to trip or shut down in response to an operational transient.
- An example would be some fault that removes the coupling of the reactor to the heat sink, which unless the reactor is shut down will lead to a rapid rise of primary circuit pressure.
- Displacement or removal of the vessel from its supports could occur due to an earthquake of exceptional magnitude or, as a result of internal shock loadings from within the vessel itself.
- The process of core degradation and melting could result at some point in molten fuel or other materials entering the lower plenum of the reactor vessel. In the TMI-2 accident some 20 tones of molten fuel ended up in this location.

c. What is China syndrome? (3 marks)

Ans:

- If it is not possible to cool the debris bed within the containment building, the debris begins to react with the concrete floor of the building and penetrates this and also the bedrock on which the reactor is built.
- This gradual downward penetration of the molten pool has colloquially been referred to as the "China Syndrome".

OR

8. a. Discuss progressive failure of fuel. (6 Marks)

Ans:

1. Fuel-coolant interactions-"steam explosions"
2. Debris beds and their cooling
3. Hydrogen formation-burning and explosions
4. Containment basemat melt-through and failure

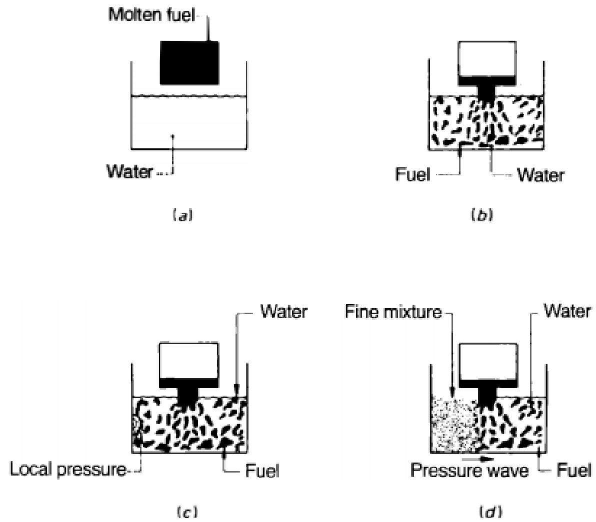
1. Fuel-Coolant Interactions: "Steam Explosions":

- Under some circumstances, rapid vaporization may cause a detonation.
- They may also occur if room-temperature water is brought into contact with liquid natural gas; in this case, the detonation may be followed by a fire as the gas cloud burns.
- The potential for an energetic interaction between molten uranium fuel and the water coolant may also exist if molten fuel is jetted into water. This can occur as:

1. molten fuel is ejected into the coolant when the cladding fails during severe power excursion
2. the lower core support plate fails and molten fuel is jetted into a pool of water in the vessel lower head
3. the lower head of the pressure vessel fails and molten fuel falls into a water-filled reactor cavity

- The molten fuel is initially above the pool of coolant and then falls into it, giving rise to coarse mixing between the fuel and the coolant with a dispersion of large elements of the molten fuel.

- They transfer heat relatively slowly to the water, since a thin vapor film forms around them and insulates them from the water coolant.
- The third stage is that of triggering a shock wave. This is often postulated to occur at the surface of the vessel and might be caused by a small, localized vapor explosion or impact.
- This shock wave then passes through the coarse fuel-coolant mixture and breaks up the fuel into small elements, which may transfer their stored energy rapidly to the coolant.
- This energy release strengthens the shock wave, which continues to propagate through the mixture in an explosive manner.



Stages of a steam explosion. (*a*) Initial condition; molten fuel and coolant separate. (*b*) Stage 1, coarse mixing; slow heat transfer, no pressure increase. (*c*) Stage 2, trigger process; local pressure, e.g. from impact or entrapment. (*d*) Stage 3, propagation; pressure wave fragments fuel very rapidly; heat transfer from fine fragments very rapid. (Gittus et al. 1982.)

- Experimental studies indicate that the efficiency of conversion from the stored energy in the fuel to the energy within the explosion is about 1 .5%.
- This would result in an explosion of roughly 1 GJ (or 200 kg TNT equivalent) if all the fuel in a PW, say, reacted simultaneously.

2. Debris Beds and Their Cooling:

- If beds of fuels can be effectively cooled, remelting is avoided and damage to the vessel or the cavity contained in the bed may be prevented.
- Some mechanisms for debris bed cooling are illustrated here:

1. Once-thorough flow through the bed:

- ✓ Liquid is able to reach the bottom of the bed and is then induced to flow into the bed under the action of natural or forced circulation.
- ✓ Natural circulation would be caused by the difference in density of the coolant inside the bed and outside the bed.
- ✓ First phase is for the heat generated in the bed to heat the liquid to its boiling point.
- ✓ Then, as the flow passes through the bed, the liquid is evaporated and ultimately converted totally to vapor.
- ✓ From this point on, the temperature rises and if the circulation is too low or the bed too deep, the particles may reach a temperature at which they begin to fuse together.

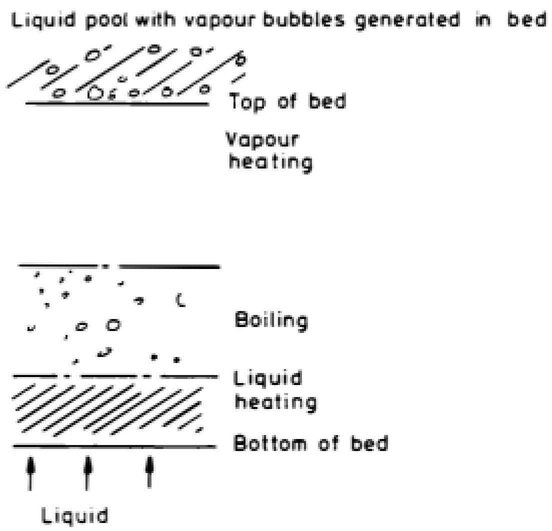
2. Cooling of closed deep beds:

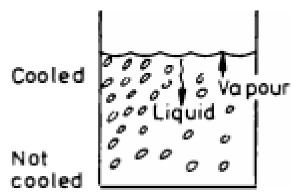
- ✓ The liquid can only enter from the top of the bed.

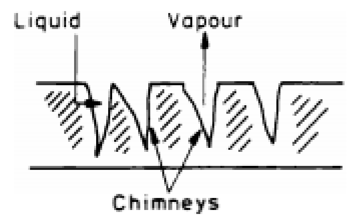
- ✓ The liquid trickles into the bed, cooling it and generating vapor, which must escape in the direction opposite to that of the liquid flowing in.
- ✓ This may mean that only the upper part of the bed is cooled and the lower part may become overheated.

3. Shallow-bed cooling:

- ✓ If there is a shallow bed of particulate material on the bottom of the containment and this is covered by a liquid layer, then "chimneys" may be formed in the layer through which the vapor may escape.
- ✓ The liquid passes into the bed by capillary action through the particulate layer between the chimneys.







3. Hydrogen Formation: Burning and Explosions:

- Hydrogen can be formed at various stages of a severe accident as a result of chemical accidents between steam and various metals which can burn or detonate, hazarding the containment systems.
- The most important contributor to the hydrogen formation process is the oxidation of the zirconium cladding of the fuel:

$$Zr + 2H_2O = Zr\ O_2 + 2H_2$$

- The reaction is exothermic adding to the decay heat.
- Other materials that react include chromium and iron and even uranium dioxide.
- Hydrogen may be formed at various phases of the accident:

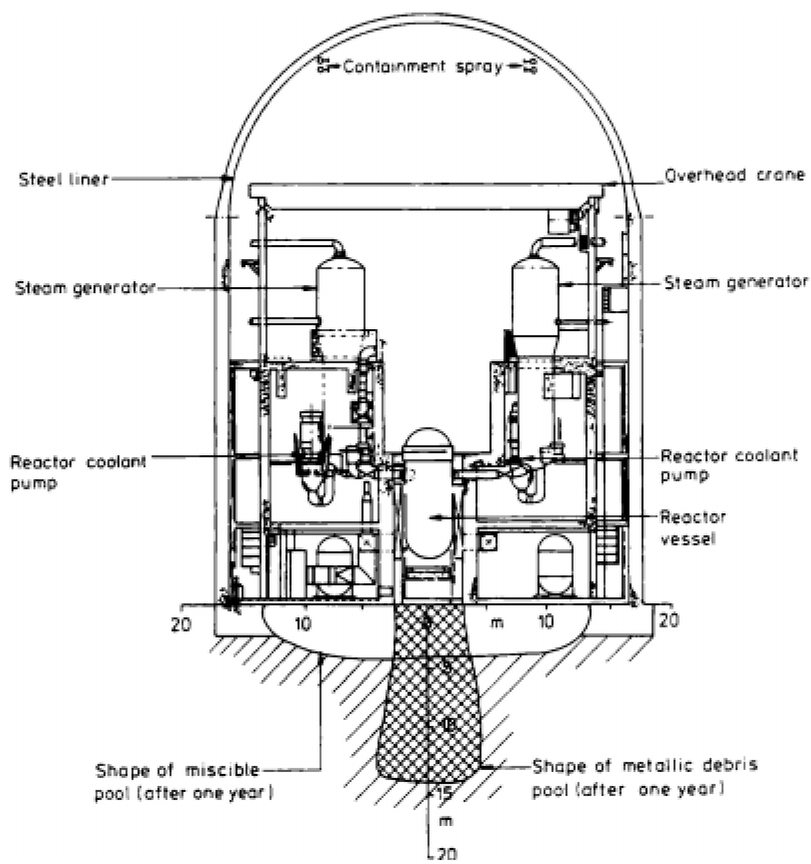
1. When the initial heat-up occurs; perhaps 20-40% of the cladding may react in the first 10 or 20 minutes
2. When further water from the ECCS system or reactor coolant pumps contacts the hot debris
3. When molten debris jets or falls into the vessel lower head and vaporizes water to steam, which then has access to relatively undamaged fuel in the core above
4. When the pressure lower head fails and the molten debris attacks the concrete of the vessel cavity and containment

- Hydrogen can react with the oxygen within the continment in one of two ways.
- The first way is by deflagration, or a diffusion flame in which the unburned gas is heated by conduction to a temperature sufficiently high for a chemical reaction.
- Whether a combustion reaction takes place depends on reaching the minimum concentration of the hydrogen, i.e., 4-9% by volume.
- In the second way, in a detonation, the unburned gas is heated by compression in a shock wave where initiation can come from a spark or other high-energy source. The consequences of a detonation depend on the concentration of the hydrogen and the geometry of the containment internals.
- One means of controlling hydrogen is to have an inert atmosphere (nitrogen) in the containment.

- Other techniques include catalytic recombiners (which react hydrogen and oxygen to form steam) and igniters installed at various locations within the containment.

4. Containment Basemat Melt-Through and Failure:

- If it is not possible to cool the debris bed within the containment building, the debris begins to react with the concrete floor of the building and penetrates this and also the bedrock on which the reactor is built.
- This gradual downward penetration of the molten pool has colloquially been referred to as the "China Syndrome".
- First, if the melt consists mainly of oxide, it is likely to be miscible with the base concrete and rock.
- A molten pool would be formed of limited depth with a diameter. This pool will remain for a period of up to several years.
- The heat generated by fission product decay within the pool is dissipated into the surrounding rock due to the temperature gradients.
- Second, if in the melting process molten steel is produced, this may dissolve fission products from the fuel.
- If this molten steel is oxidized, the melt pool will be miscible with the concrete-rock base and a pool formed.
- If the steel is not oxidized, the steel-fission product solution will not be miscible with molten fuel and concrete-rock and will itself penetrate the base rock much farther.
- Interaction between the molten fuel and the concrete-rock will result in the release of significant amounts of vapor and gas as a result of the chemical reaction.
- This may result in pressurization of the containment building over a long period of time, particularly if no cooling is available.



Typical PWR containment showing shapes of meltdown pool after 1 year.

b. Differentiate between on load refueling and off load refueling. (4 Marks)

Ans:

- A basic decision in the design of any nuclear reactor is whether to remove and insert fuel while the reactor is operating **(on-load refueling**)or when the reactor is shut down **(off-load refueling**).
- On-load refueling is much more complex, and the cost of the equipment is high.
- On the other hand, total shutdown of the reactor system for a significant period to allow off-load refueling leads to a loss of electrical power output, and this in itself is very expensive.
- In general, reactors that have a large throughput of fuel, such as natural uranium reactors like Magnox and CANDU operate with on-load refueling
- Those with a lower throughput of enriched fuel like PWR and BWR tend to use off-load refueling.
- The Advanced Gas-Cooled Reactor (AGR) is intermediate between these two cases; it has the capability of on-load refueling also.
- For fast reactors, off-load refueling is necessary because of the very large changes in reactivity with any fuel movements during operation.

c. Discuss reprocessing of spent fuel. (6 Marks)

Ans:

- If it has been decided to reprocess spent fuel with the objective of recovering valuable uranium and plutonium, the fuel must first be transported to a reprocessing plant using the flasks described in the previous section.
- In a modern reprocessing plant like THOR (Thermal Oide Reprocessing Rant) operated by British Nuclear Fuels at Sellafield, the actual separation process is undertaken after at least 5 years' storage of the spent fuel in the ponds.
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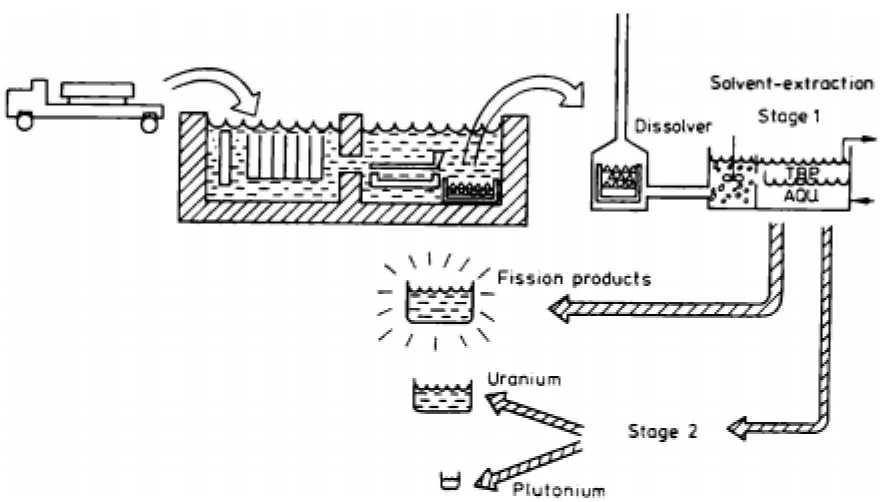


Schematic diagram of reprocessing plant.

<u>MODULE-5</u>

9. a. List the fission products & discuss their biological significance. (8 Marks)

<u>Ans:</u>

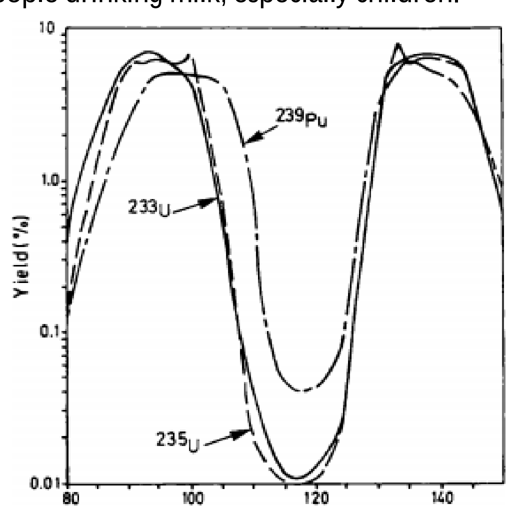
- Radioactive wastes can arise in gaseous, liquid, or solid forms.
- At some stage of the management process the radioactivity in the gaseous and liquid form is converted into a solid form.

- Most attention is therefore directed at the disposal of solid waste.
- Essentially, waste products from nuclear power may arise as follows:

1. **Uranium Mining:** The spoil from uranium mining is mildly radioactive and may need stabilization and monitoring.
2. **Fuel Fabrication Plant**. The enrichment and fabrication plants for uranium-based fuel present no particular problems in terms of radiation hazard. However, the fabrication of plutonium-based fuel produces low-activity plutonium-bearing residues of wastes arising from the fabrication process.
3. **Spent Nuclear Fuel:** Spent nuclear fuel includes the highly radioactive fuel matrix together with the fuel can and supporting grids. The matrix itself contains the highly radioactive fission products, the remaining part of the original fissile and fertile materials, and the material bred in the reaction. Even if the fissile and fertile materials are recycled, the highly radioactive fission products remain and are the most important wastes arising from nuclear power.
4. **Reprocessing Plant:** Reprocessing produces recycled product streams (uranium and plutonium), the fission product stream, aqueous and organic streams containing medium levels of radioactivity. Another waste product is the residual cladding and support materials from the fuel elements, often referred to as hulls.
5. **Nuclear Reactors:** Other radioactive products come from the reactors themselves. These include gaseous wastes (such as Xenon and Krypton) from defective fuel, liquid wastes such as tritium oxide (the form of water produced from the tritium isotope of hydrogen), solid wastes such as the resins from the water treatment plants, and the filters from the clean-up system in a gas-cooled reactor. Finally, when the reactor comes to the end of its useful life, it must be decommissioned.

FISSION PRODUCTS AND THEIR BIOLOGICAL SIGNIFICANCE:

- Fission products range in atomic mass from about 80 to 160.
- For each kilogram of fissile material converted, a certain percentage is converted to one pair of fission products, a certain percentage to another, and so on.
- Typically, there are about 40 possible fission reactions producing about 80 different species of fission product.
- Isotopes that released would be absorbed and concentrated in specific organs of the body.
- Various radioactive isotopes of iodine are formed in the fission reaction, or are subsequently formed by decay of other fission products, can concentrate in the thyroid gland.
- In general, the longer the half-life, the less intense the radiation.
- In an accidental release it might be expected that iodine would deposit on grassland, be eaten by cows, appear in the milk, and be taken up by people drinking milk, especially children.



Mass-yield curves for thermal-neutron fission of U^{233}, U^{235}, and Pu^{239}.

- Biological half-life is the time needed for any particular radioactive element, taken into the body, to be reduced to half its level of natural excretion processes.
- Caesium-137 and Strontium-90 isotopes have radioactive half-lives of approximately 30 years.
- However, the biological half-lives are around 70 days for Cesium and 50 years for Strontium.
- The long biological half-life of strontium is due to the fact that it accumulates in the bone structure. Thus, strontium is considered a more serious hazard than Cesium.
- Plutonium-239 also has a long biological half-life i.e. 200 years in the bone structure and 500 days in the lung.
- Another important radioisotope, Tritium, is emitted in small quantities from water reactors and reprocessing plants by the process of ternary fission, in which three, rather than the usual two, fission products are formed.
- Its molecular size is very small &it can emit beta radiation and has a radioactive half-life of 12.6 years. Its biological half-life is around 12 days.
- Nuclear reactions also produce heavy elements (actinides) whose atomic weight is equal to or higher than that of the uranium isotope from which they are formed.
- The actinide elements are important in nuclear waste because of their relatively long half-lives, ranging from 17 years for Cm244 to 25,000 years for Pu239.

1. Fuel discharged from a light -water reactor without reprocessing. Here, the hazard of the waste falls below that of the original ore after 10,000 years.
2. Waste arising from normal reprocessing in which 0.5% of the uranium and plutonium are assumed to be contained in the waste. The hazard level falls to around that of the original ore after about 500 years. It is assumed that 99.5% of the plutonium extracted is used in fast reactors and that the fuel from these reactors would be reprocessed, giving a somewhat similar curve in terms of hazard as a function of time.
3. Waste from thermal reactor fuel in which the plutonium from the reprocessing plant has been incorporated. The hazard is intermediate between those in the first two cases above and falls to that of the original ore after about 1000 years.

- Hazard falls rapidly after about 100 years for all the cases, reflecting the decay of significant amounts of the shorter-lived fission products.

b. Explain the fusion process. (8 Marks)

- The energy generated by the sun is not the result of splitting up nuclei of heavy elements but of the joining together-fusion--of nuclei of light elements such as the isotopes of hydrogen or lithium.

THE FUSION PROCESS:

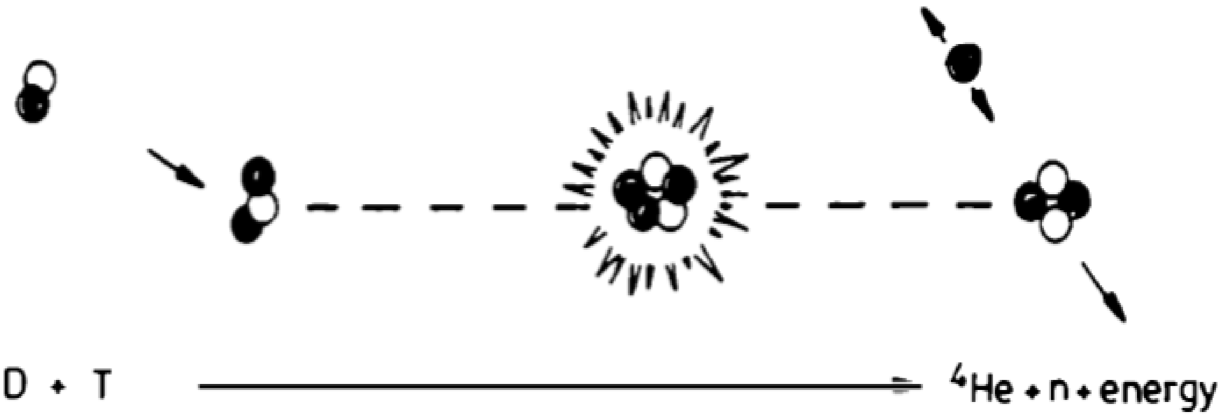
- Faster fusion reactions are possible with a range of mixtures involving the isotopes of hydrogen, helium, and lithium.

$$^{2}D + {}^{2}D \rightarrow {}^{2}He + n + 0.96 \times 10^{-13}\ J$$

$$^{2}D + {}^{2}D \rightarrow {}^{2}T + {}^{1}H + 1.19 \times 10^{-13}\ J$$

$$^{2}D + {}^{3}D \rightarrow {}^{4}He + n + 5.2 \times 10^{-13}\ J$$

- Most (80%) of the energy released is in the form of kinetic energy of the neutron.
- Note that though the energy released per fusion reaction is typically 10 times less than for a single fission reaction the neutrons are released with perhaps 5 times as much energy.

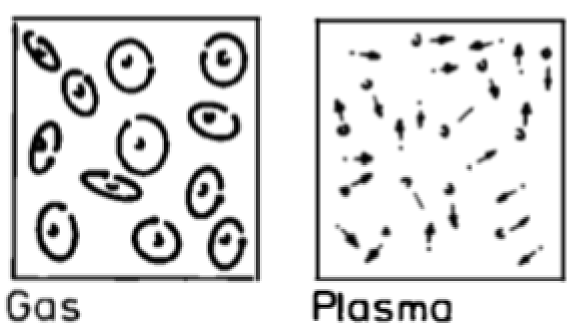


- Deuterium occurs in ordinary water at a concentration of 0.016% and can be readily separated by chemical processes.
- Tritium does not occur naturally but can be produced from lithium by bombardment with a neutron.

$$^{6}Li + n \rightarrow {}^{4}He + {}^{3}T + 7.7 \times 10^{-13}\ J$$

$$^{7}Li + n \rightarrow {}^{4}He + {}^{3}T + n - 4.0 \times 10^{-13}\ J$$

- In a blanket it is possible to arrange the system so that neutrons from the fusion reaction are used to breed more tritium from these reactions.
- The fusion reaction is difficult to achieve because the deuterium and tritium nuclei are each positively charged electrically.
- Like charges repel each other and this force can be overcome only if the nuclei approach each other with sufficient velocity-millions of kilometers an hour-to overcome the mutual repulsion.
- That means heating up the gaseous deuterium-tritium mixture to a temperature around 100 million degrees or more.
- At a temperature of a few thousand degrees the gas becomes ionized; that is, the electrons separate from the atoms and the separate electrons and nuclei move randomly.
- Such material is known as **Plasma.**



- It is not enough to heat the plasma to the required temperature.
- It is also necessary to hold the plasma at that temperature for sufficient time for the reaction to take place.
- Clearly, the length of time will depend on the number of nuclei in a given volume of plasma.
- The required conditions have been identified in the Lawson criterion, which states that the product of the time for which the plasma is confined ζ_F and the density of the plasma (n) must be greater than 10^{20} s/m^3 .

$$n \times \tau > 10^{20}\ s/m^2$$

- Thus, if the density of the plasma is 10^{20} nuclei per cubic meter, the plasma must be held at 100-200 million degrees for 1 s.

OR

10. a. Explain the options for management of high level active waste. (8 Marks)

Ans:

- Themost important source of radioactive waste products is the fuel itself.
- There are two alternative routes for dealing with the spent fuel.
- In route A the fuel is passed through a reprocessing plant, which allows recycling of the plutonium and uranium and produces a highly active liquid waste stream.
- This latter stream may be passed to an interim liquidstorage stage, followed by solidification in one form or another, before being passed to an engineered surface store, where it is kept for about 50 years.
- In route B the spent fuel is stored either at the reactor site or away from it in a specially engineered spent fuel store, before ultimate geological disposal.

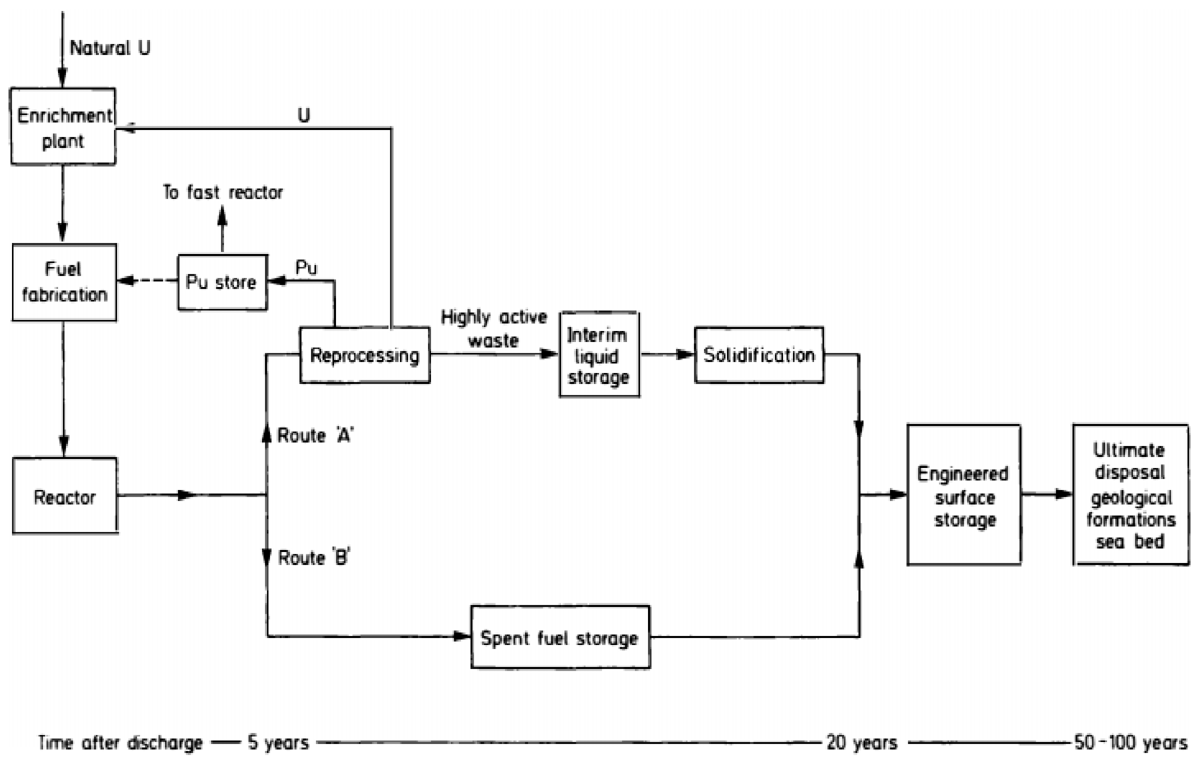


Figure 8.3: Options for management of high-level active wastes.

LONG-TERM STORAGE AND DISPOSAL OF SPENT NUCLEAR FUEL:

- It is possible to continue with away-from-reactor underwater storage, perhaps with the fuel contained in an additional "bottle" to prevent the spread of contamination within such a large water basin store.
- Essentially, two different dry storage systems have been developed: **the cask or container system** and **the modular vault dry store**.
- The latest design of dry storage container is shown:

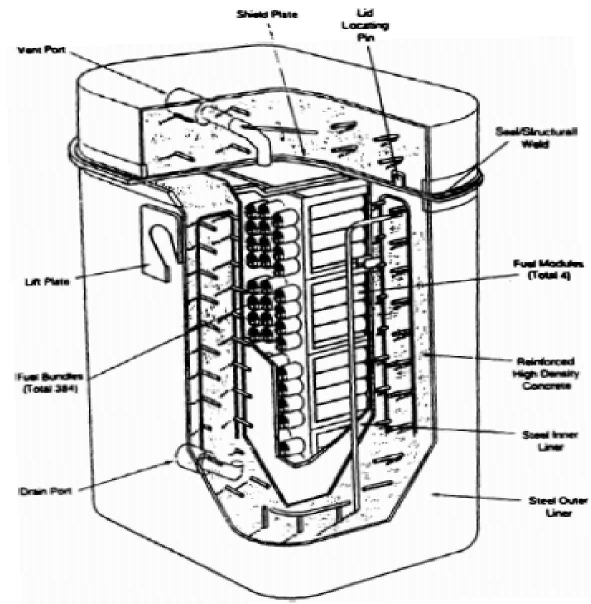
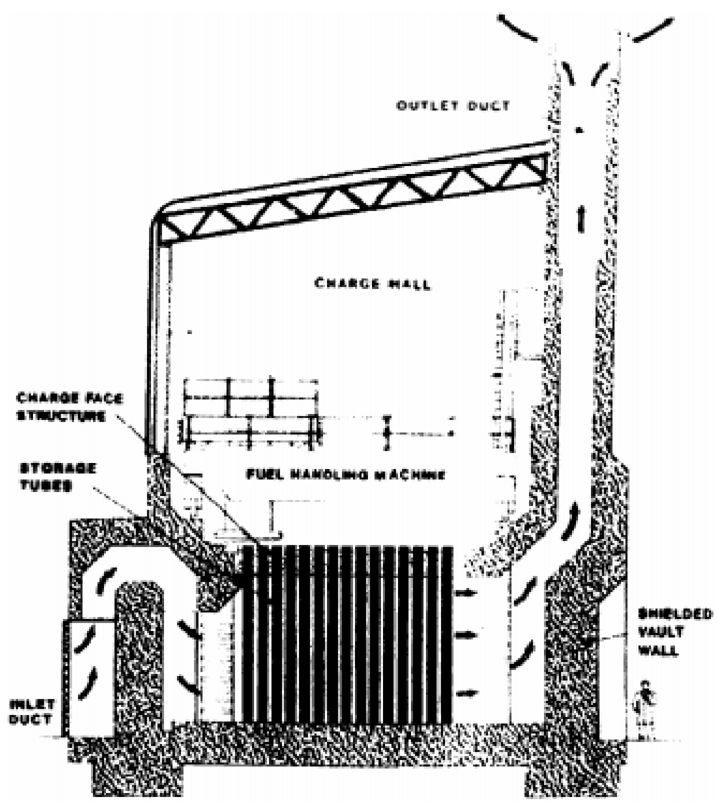


Figure 8.4: Dry storage container for spent CANDU fuel.

- It consists of a box 25 m x 2 m x 3.5 m high, constructed from inner and outer steel shells filled with heavy concrete.
- Spent fuels are stored horizontally in four racks.
- In a modular vault dry store the spent fuel is contained in individual vertical sealed fuel storage tubes retained within a concrete vault that can be constructed in modules.
- Air is drawn in by natural circulation between the arrays of storage tubes and is discharged via an outlet duct.
- The coolant air does not come in contact with the spent fuel and therefore neither it nor the concrete structure becomes contaminated.



Modular vault dry storage system.

- This design has 45 fuel storage tubes, each holding six fuel elements.

- The fuel is moved in and out of the storage tubes by a fuel handling machine moved by the building crane.
- The concepts being considered for ultimate disposal are given below.

1. **Ultimate Disposal in Salt Deposits:**

- Salt deposits are attractive sites for long-term disposal of radioactive waste.
- Fuel placed in such a deposit would be free from the leaching action of the groundwater.
- Salt is present in the solid form in a geological stratum indicates that it has been free from circulating groundwater since its formation several hundred million years ago.
- Typically, a PWR fuel element may be generating 500 watts of decay heat after 10 years, and this heat generation declines with a half-life of about 30 years since the heat release is dominated by the strontium and caesium decays.

2. **Geological Storage:**

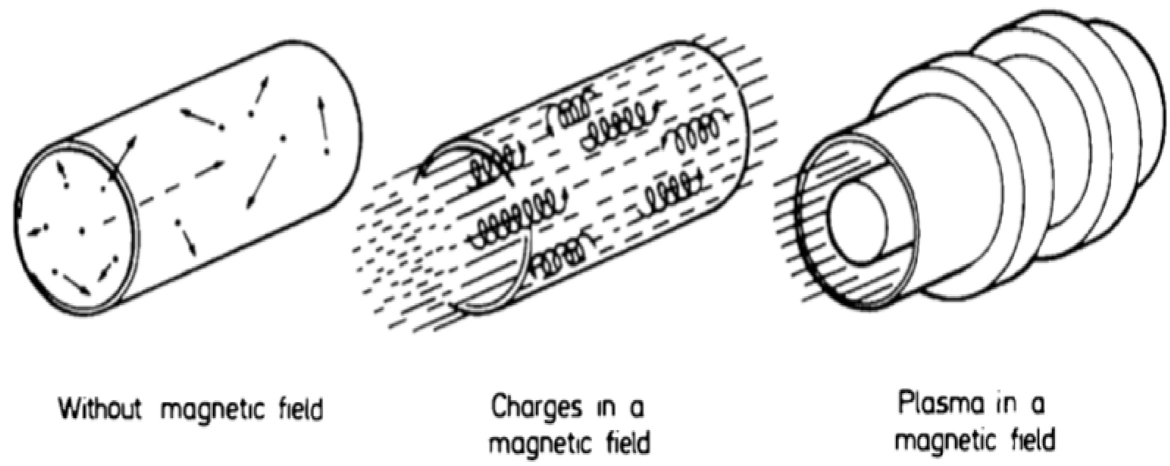
- Geological storage involves the placement of the canisters containing spent fuel elements in a stable stratum typically 1 km below the surface.
- Such rocks can be assumed to contain water, since the depth would be well below the water table.
- However, the water is not expected to play a large role in the heat transfer from the blocks, and the store would be designed to maintain the surface temperature of the canisters at no more than 100°C or so.
- However, the presence of groundwater means that material that is leached from the storage blocks may be transported through the stratum in the water and this is an important consideration in the design of such systems.
- Circulation of water through the rock as a result of density differences induced by Temperature gradients over long period is important in determining the migration of the fission products.
- This is a very slow process and is not expected to present a serious hazard, but it must be very carefully taken into account for long-term disposal systems.

b. What is confinement of plasma? What are the methods to provide confinement? (8 Marks)

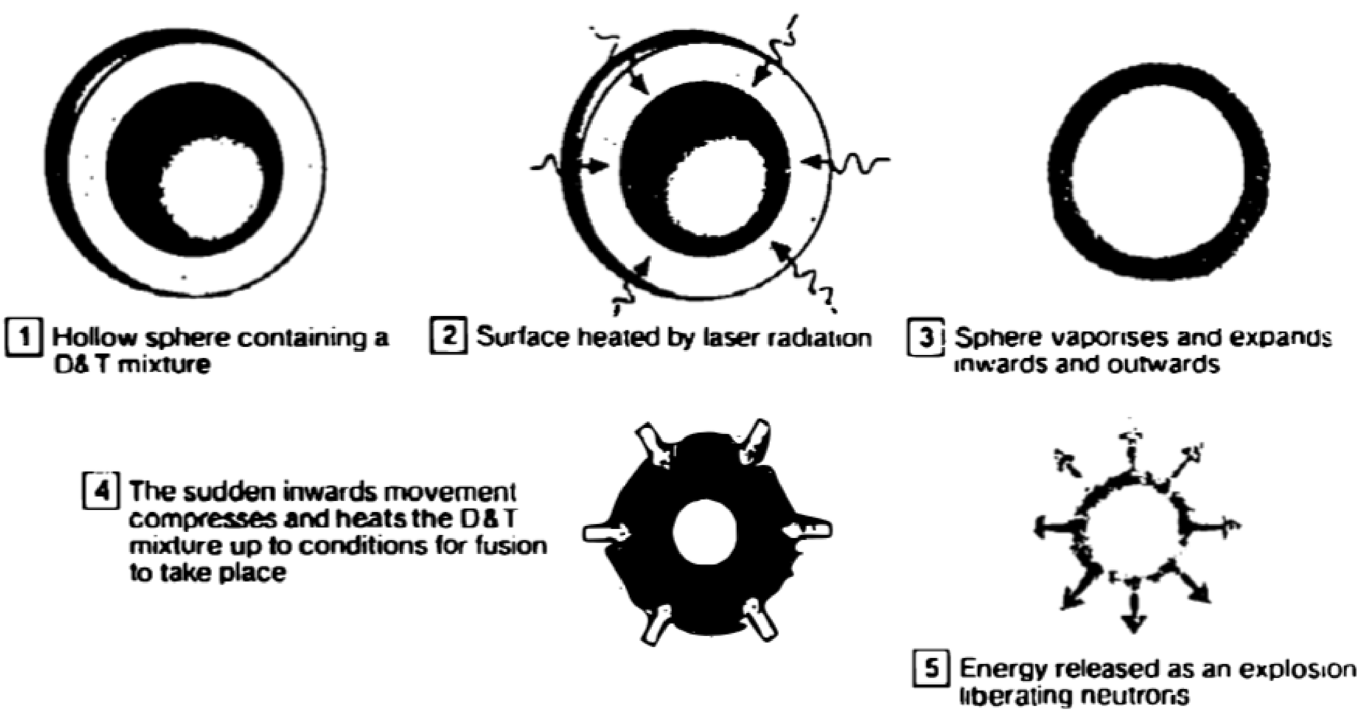
Ans:

- In the Sun and stars the fusion plasma is held together by large gravitational forces.
- On Earth we obviously cannot use such forces to contain plasma in any convenient-sized apparatus.
- Two ways have been tried to provide this confinement of the plasma.

1. **Magnetic confinement:**
   - ✓ Since plasmas are excellent conductors of electricity magnetic fields can be used to shape and confine the plasma in such a manner that it does not touch the walls of the vessel in which the gaseous mixture is held.
   - ✓ If the plasma did come into contact with the vessel walls, it would quench, losing its energy and high temperature very rapidly.

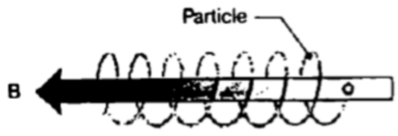


2. **Inertial confinement:**
   - ✓ The alternative to magnetic confinement is to contain the isotopic mixture frozen solid at about 15 K as a small spherical pellet or bead.
   - ✓ This spherical pellet is then bombarded from every direction by beams of high-powered lasers, which compress and heat the mixture to fusion temperatures.
   - ✓ Inertia holds it together long enough-perhaps a nanosecond (10-9s) for the fusion reaction to take place.
   - ✓ Fundamental difficulties with this route to a practical system are the low efficiency of the laser (1-2%), the low fraction of fusion energy released to date (~0.01%), and the difficulties of engineering a device to produce a continuous power output involving ignition of a stream of frozen pellets at a high rate.



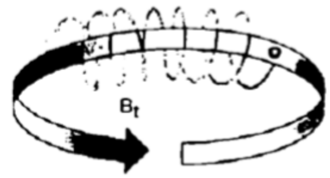
- A fusion reaction using magnetic confinement is therefore used in majority cases.

a

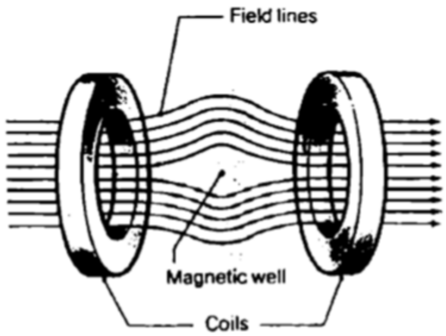


A charged particle will gyrate around a magnetic field line B.
This is the **Basic Mechanism** whereby a magnetic field **confines a plasma.**

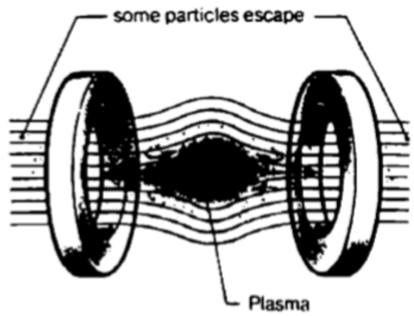
b



In a Toroidal system the field lines, B_t are bent back on themselves to form a closed loop.



In an 'open' system the field lines do not form a closed loop within the device.



The bulk of the particles form a plasma sitting in the Magnetic Well. Some particles have high longitudinal energy and can escape out the ends.

- The structure of magnetic fields is often indicated by lines of force or field lines i.e. the stronger the field, the greater the density of the lines.
- A magnetic field line causes a charged nucleus to spiral around it.
- If the field is arranged so as to close on itself in a circle within a circular chamber, the particles will spiral around the field and remain trapped within the circular chamber, or toms.
- Unfortunately, this does not always happen in practice due to instabilities that occur in the plasma.
- Another possibility is to constrict the magnetic field lines at each end of a tube.
- Panicles trying to escape by spiraling along the field lines are reflected back into the central region.
- This arrangement is called a magnetic mirror or bottle.