



# HL IB Physics

  
Your notes

## Fission

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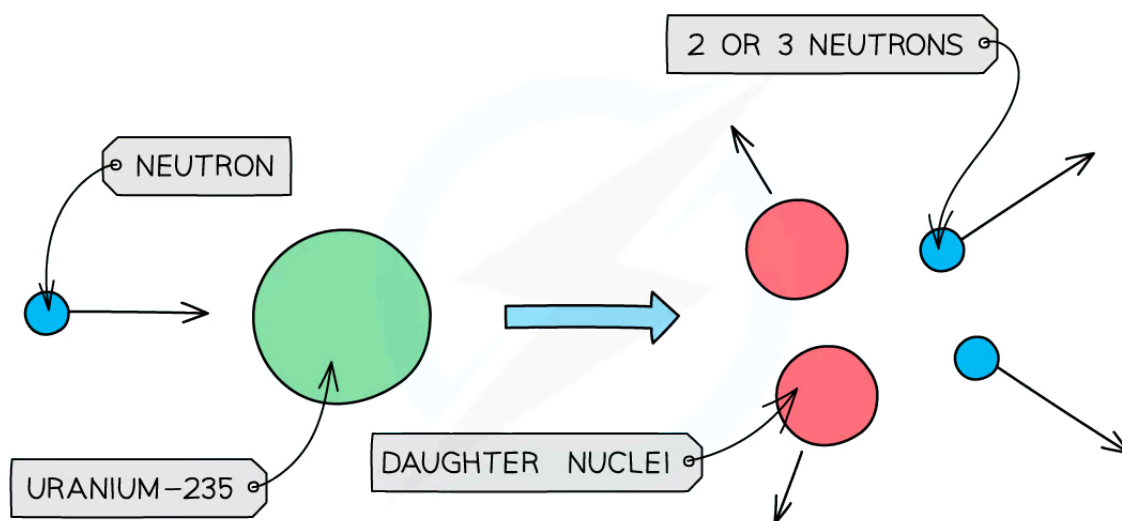
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## Spontaneous & Induced Fission

### Spontaneous & Induced Fission

- There is a lot of energy stored within the nucleus of an atom
  - This energy can be released in a nuclear reaction such as **fission** or **fusion**
- Nuclear fission is defined as:
 

**The splitting of a large, unstable nucleus into two smaller nuclei**
- Isotopes of **uranium** and **plutonium** both undergo fission and are used as fuels in nuclear power stations to convert nuclear energy into electrical energy
- During fission, when a neutron collides with an unstable nucleus, the nucleus splits into **two smaller nuclei** (called daughter nuclei) as well as **two or three neutrons**
  - Gamma rays are also emitted



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**Large nuclei can decay by fission to produce smaller nuclei and neutrons with a lot of kinetic energy**

- The products of fission move away very **quickly**
- This is because energy is transferred from the **nuclear potential energy** store of a nucleus to the **kinetic energy** store of the fission fragments
  - This energy is then carried away as **heat**

### Spontaneous Fission

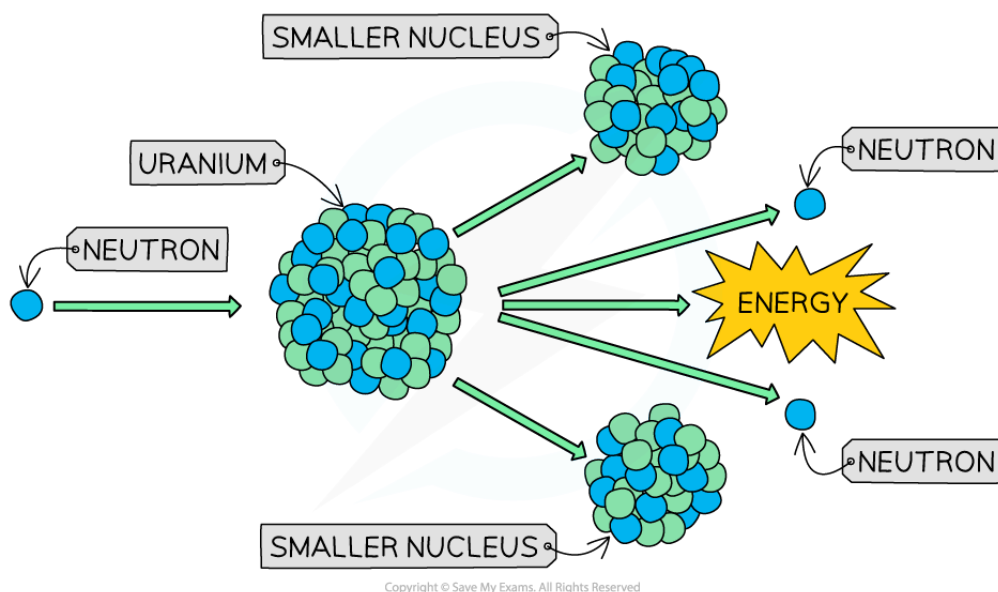
- It is **rare** for nuclei to undergo fission without additional energy being put into the nucleus
- When nuclear fission occurs in this way it is called **spontaneous fission**



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## Induced Fission

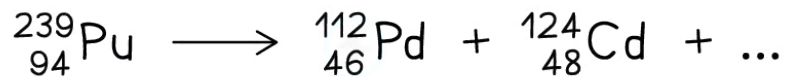
- Usually, for fission to occur the unstable nucleus must first **absorb** a **neutron**
  - This will be slow moving, often called a 'thermal' neutron
- Take, for example, uranium-235, which is commonly used as a fuel in nuclear reactors
- It has a very long half-life of 700 million years
- This means that it would have low activity and energy would be released only if it was to have additional neutrons added



- During induced fission, a **neutron** is absorbed by the uranium-235 nucleus to make uranium-236
  - This is very unstable and splits by nuclear fission almost immediately

### Worked example

During a particular spontaneous fission reaction, plutonium-239 splits as shown in the equation below:



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Which answer shows the section missing from this equation?

A	${}_{0}^{3}\text{n}$
B	${}_{0}^{0}\gamma$
C	${}_{2}^{4}\alpha$
D	$3{}_{0}^{1}\text{n}$

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**ANSWER: D**

#### Step 1: Identify the different mass and atomic numbers

- Pu (Plutonium) has mass number 239 and atomic number 94
- Pd (Palladium) has mass number 112 and atomic number 46
- Cd (Cadmium) has mass number 124 and atomic number 48

#### Step 2: Calculate the mass and atomic number of the missing section

- Mass number is equal to the difference between the mass numbers of the reactants and the products

$$239 - (112 + 124) = 3$$

- Atomic number is equal to the difference between the atomic numbers of the reactants and the products

$$94 - (46 + 48) = 0$$

- The answer is therefore not **B** or **C**

#### Step 3: Determine the correct notation

- Neutrons have a mass number of 1
- The answer is therefore not **A**

- Therefore, this must be three neutrons, which corresponds to D



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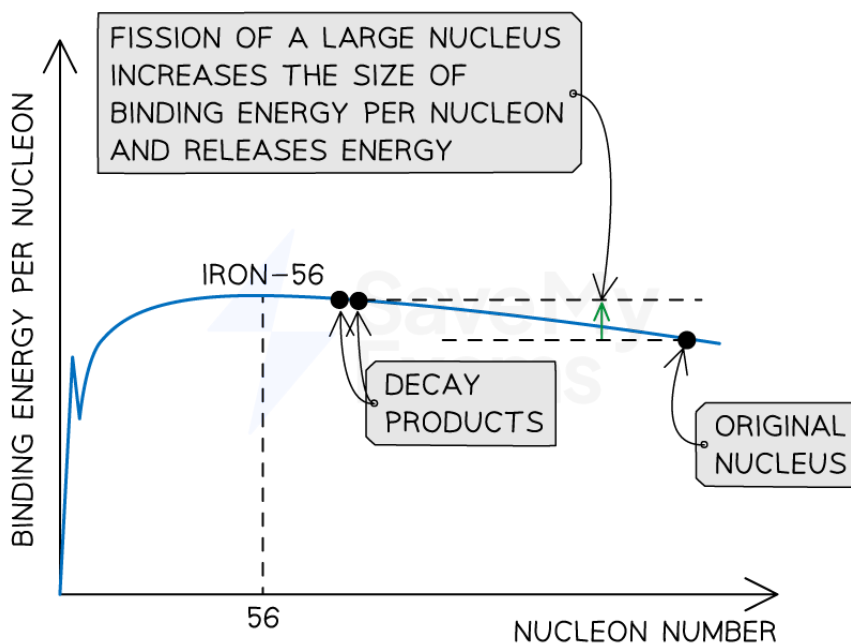


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## Energy Released in Fission Reactions

### Energy Released in Fission Reactions

- When a large (parent) nucleus, such as uranium-235, undergoes a fission reaction, the daughter nuclei produced as a result will have a **higher binding energy per nucleon** than the parent nucleus
- As a result of the mass defect between the parent nucleus and the daughter nuclei, **energy is released**



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**Energy can be extracted from fission reactions due to the mass defect between parent and daughter nuclei**

- Nuclear fission is well-regarded as having the fuel source with the **highest energy density** of any fuel that is currently available to us (until fusion reactions become feasible)

#### Examples of Common Fuels: Energy Density and Specific Energy Table



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Fuel	Specific energy (MJ kg <sup>-1</sup> )	Energy density (MJ m <sup>-3</sup> )
Coal	35	2 × 10 <sup>4</sup>
Hydrogen	130	10
Kerosene	48	3.3 × 10 <sup>4</sup>
Gasoline (petrol)	45	3.4 × 10 <sup>4</sup>
Wood	15.5	1 × 10 <sup>4</sup>
Uranium-235 (fission)	7.5 × 10 <sup>7</sup>	4 × 10 <sup>13</sup>

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- Calculations involving energy released in fission reactions often require the use of equations found in an array of previous topics, such as

$$\text{density (kg m}^{-3}\text{)} = \frac{\text{energy density (J m}^{-3}\text{)}}{\text{specific energy (J kg}^{-1}\text{)}}$$

$$\text{no. of atoms} = \frac{\text{mass (g)} \times \text{Avogadro's number } N_A \text{ (mol}^{-1}\text{)}}{\text{molar mass (g mol}^{-1}\text{)}}$$

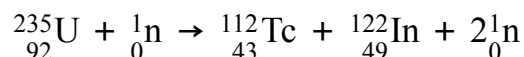


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### Worked example

When a uranium-235 nucleus absorbs a slow-moving neutron and undergoes a fission reaction, one possible pair of fission fragments is technetium-112 and indium-122.

The equation for this process, and the binding energy per nucleon for each isotope, are shown below.



nucleus	binding energy per nucleon / MeV
${}_{92}^{235}\text{U}$	7.59
${}_{43}^{112}\text{Tc}$	8.36
${}_{49}^{122}\text{In}$	8.51

- Calculate the energy released per fission of uranium-235, in MeV.
- Determine the mass of uranium-235 required per day to run a 500 MW power plant at 35% efficiency.
- The specific energy of coal is approximately  $35 \text{ MJ kg}^{-1}$ .

For the same power plant, estimate the ratio

$$\frac{\text{mass of coal required per day}}{\text{mass of } {}^{235}\text{U} \text{ required per day}}$$

**Answer:**

- (a) Energy released per fission of uranium-235

#### Step 1: Determine the binding energies of the nuclei before and after the reaction

- Binding energy is equal to binding energy per nucleon  $\times$  mass number
- Binding energy before ( ${}^{235}\text{U}$ ) =  $235 \times 7.59 = 1784 \text{ MeV}$
- Binding energy after ( ${}^{112}\text{Tc} + {}^{122}\text{In}$ ) =  $(112 \times 8.36) + (122 \times 8.51) = 1975 \text{ MeV}$

#### Step 2: Find the difference to obtain the energy released per fission reaction

- Therefore, the energy released per fission =  $1975 - 1784 = 191 \text{ MeV}$





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(b) Mass of uranium-235 required per day

**Step 1: List the known quantities**

- Avogadro's number,  $N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$
- Molar mass of U-235,  $m_r = 235 \text{ g mol}^{-1}$
- Power output,  $P_{out} = 500 \text{ MW} = 500 \times 10^6 \text{ J s}^{-1}$
- Efficiency,  $e = 35\% = 0.35$
- Time,  $t = 1 \text{ day} = 60 \times 60 \times 24 = 86\,400 \text{ s}$

**Step 2: Determine the number of atoms in 1 kg of U-235**

- There are  $N_A$  (Avogadro's number) atoms in 1 mol of U-235, which is equal to a mass of 235 g

$$\text{number of atoms} = \frac{\text{mass (g)} \times N_A \text{ (mol}^{-1}\text{)}}{m_r \text{ (g mol}^{-1}\text{)}}$$

- A mass of 1 kg (1000 g) of U-235 contains  $\frac{1000 \times (6.02 \times 10^{23})}{235} = 2.562 \times 10^{24} \text{ atoms kg}^{-1}$

**Step 3: Determine the specific energy of U-235**

- Specific energy of U-235 = total amount of energy released by 1 kg of U-235
- Specific energy of U-235 = (number of atoms per kg)  $\times$  (energy released per atom) = energy released per kg
- Energy released per atom of U-235 = 191 MeV
- Therefore, specific energy of U-235 =  $(2.562 \times 10^{24}) \times 191 = 4.893 \times 10^{26} \text{ MeV kg}^{-1}$
- To convert 1 MeV =  $10^6 \times (1.6 \times 10^{-19}) \text{ J}$
- Specific energy of U-235 =  $(4.893 \times 10^{26}) \times 10^6 \times (1.6 \times 10^{-19}) = 7.83 \times 10^{13} \text{ J kg}^{-1}$

**Step 4: Use the relationship between power, energy and efficiency to determine the mass**

- The input power required is:

$$\text{efficiency \& power: } e = \frac{P_{out}}{P_{in}} \Rightarrow P_{in} = \frac{P_{out}}{e}$$

$$\text{input power: } P_{in} = \frac{500}{0.35} = 1429 \text{ MW}$$

$$\text{input power: } P_{in} = \frac{E_{in}}{t} = 1429 \times 10^6 \text{ J s}^{-1}$$

- Therefore, the mass of U-235 required in a day is:



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$$\text{mass of } ^{235}\text{U} (\text{kg s}^{-1}) = \frac{E_{in} (\text{J})}{1 \text{ s}} \times \frac{1 \text{ kg}}{\text{specific energy of } ^{235}\text{U} (\text{J})}$$

mass of U-235 (per second) =

$$\frac{1429 \times 10^6}{1} \times \frac{1}{7.83 \times 10^{13}} = 1.82 \times 10^{-5} \text{ kg s}^{-1}$$

mass of U-235 (per day) =  $(1.82 \times 10^{-5}) \times 86\,400 = 1.58 \text{ kg}$

- Therefore, **1.58 kg of uranium-235** is required per day to run a 500 MW power plant at 35% efficiency

(c) Ratio of the masses of coal and U-235

- Since specific energy  $\propto \frac{1}{\text{mass}}$

$$\frac{\text{specific energy of } ^{235}\text{U}}{\text{specific energy of coal}} \propto \frac{\text{mass of coal required per day}}{\text{mass of } ^{235}\text{U required per day}}$$

- Where the energy density of coal =  $35 \text{ MJ kg}^{-1}$

$$\frac{\text{mass of coal required per day}}{\text{mass of } ^{235}\text{U required per day}} = \frac{7.83 \times 10^{13}}{35 \times 10^6} = 2.24 \times 10^6$$

- Over **2 million times** ( $\sim 3.5 \times 10^6 \text{ kg}$ ) more coal is required than uranium-235 to achieve the same power output in a day (or second, or month or year)

### Examiner Tip

If you need to brush up on binding energy calculations, take a look at the Mass Defect & Nuclear Binding Energy revision notes.

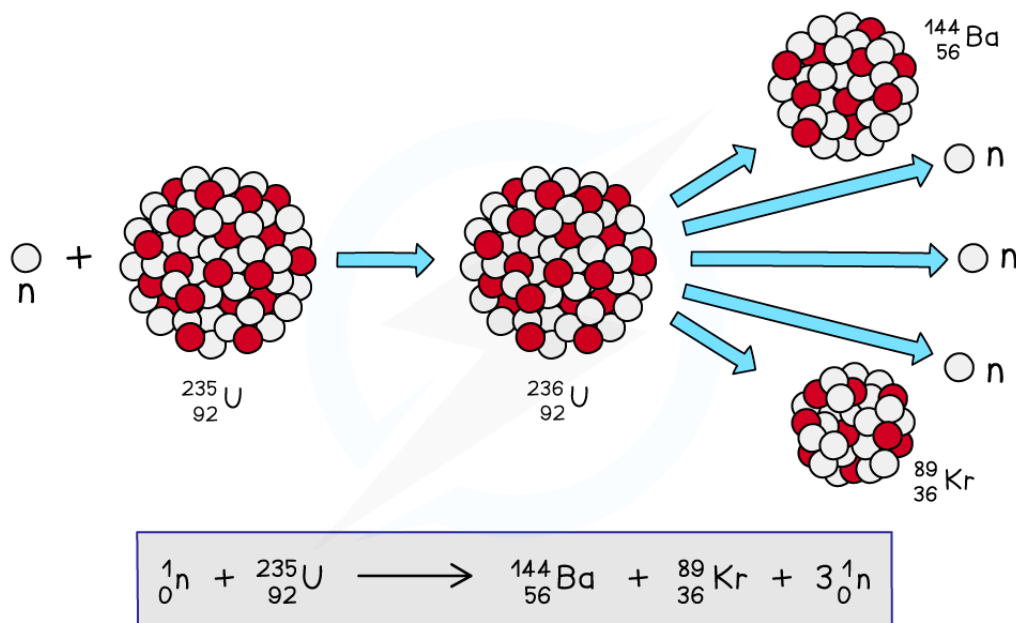


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## Chain Reactions from Fission

### Chain Reactions

- One of the many decay reactions uranium-235 can undergo is shown below:



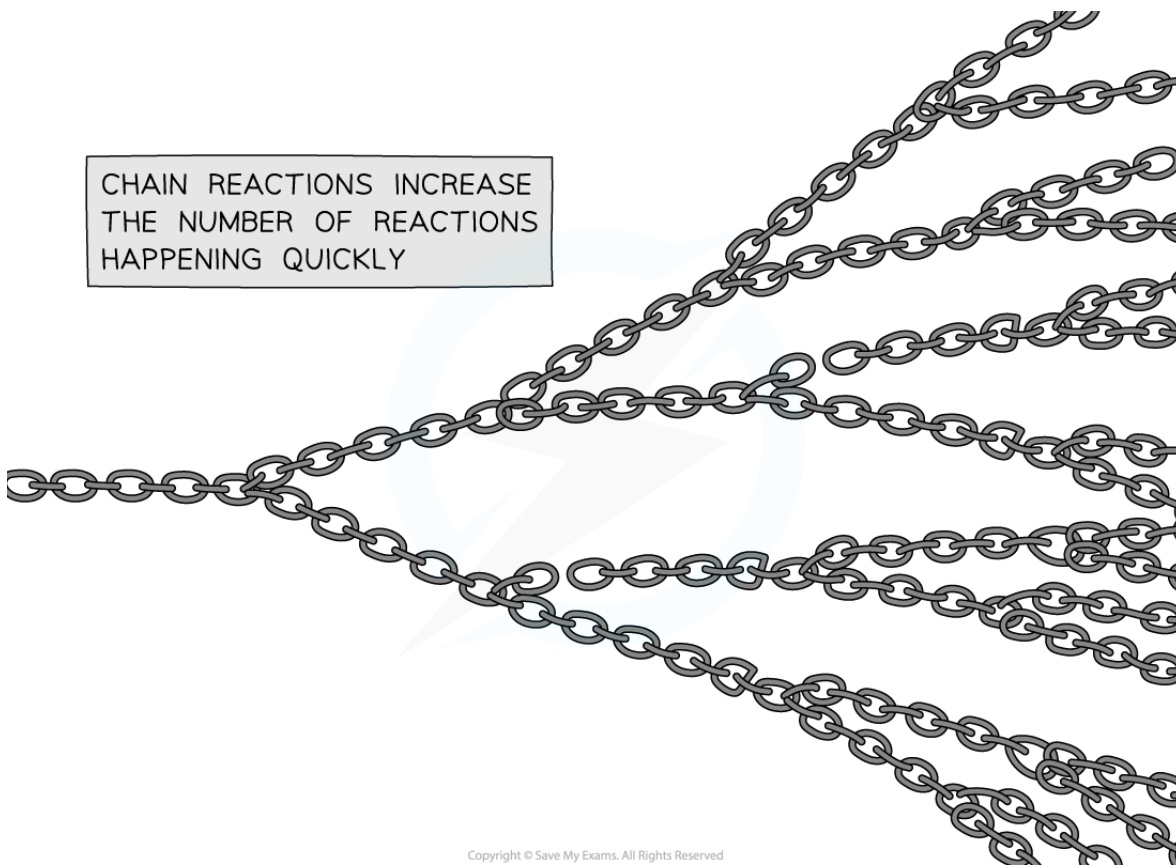
#### *Uranium-235 decay chain from nuclear fission*

- Neutrons involved in induced fission are known as **thermal neutrons**
- Thermal neutrons have low energy and speed meaning they can induce fission
  - This is important as neutrons with too much energy will rebound away from the uranium-235 nucleus and fission will not take place
- Only one extra neutron is required to induce a Uranium-235 nucleus to split by fission
- During the fission, it produces two or three neutrons which move away at high speed
- Each of these new neutrons can start another fission reaction, which again creates further **excess neutrons**
- This process is called a **chain reaction**



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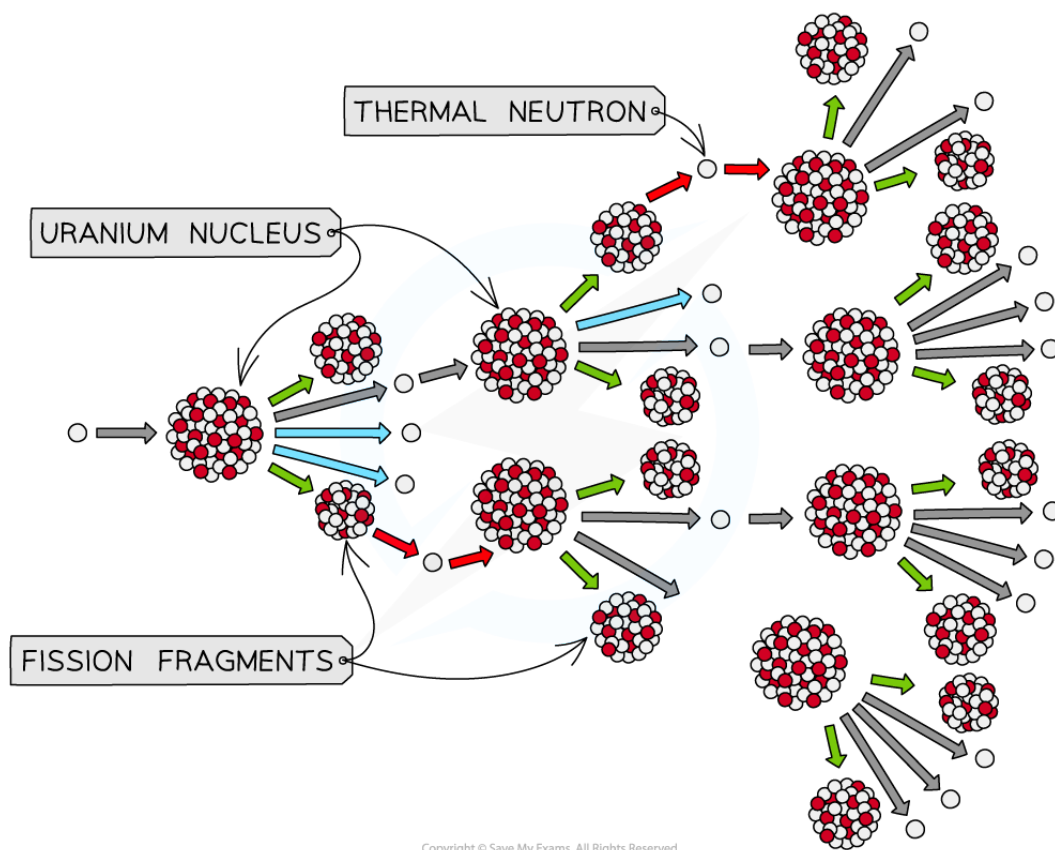
CHAIN REACTIONS INCREASE  
THE NUMBER OF REACTIONS  
HAPPENING QUICKLY



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*The neutrons released by each fission reaction can go on to create further fissions, like a chain that is linked several times – from each chain comes two more*

- The products of fission are two daughter nuclei and **at least one neutron**
- The neutrons released during fission go on to cause more fission reactions leading to a **chain reaction**, where each fission goes on to cause at least one more fission



*Only one thermal neutron is used to create another fission reaction in a controlled chain reaction*

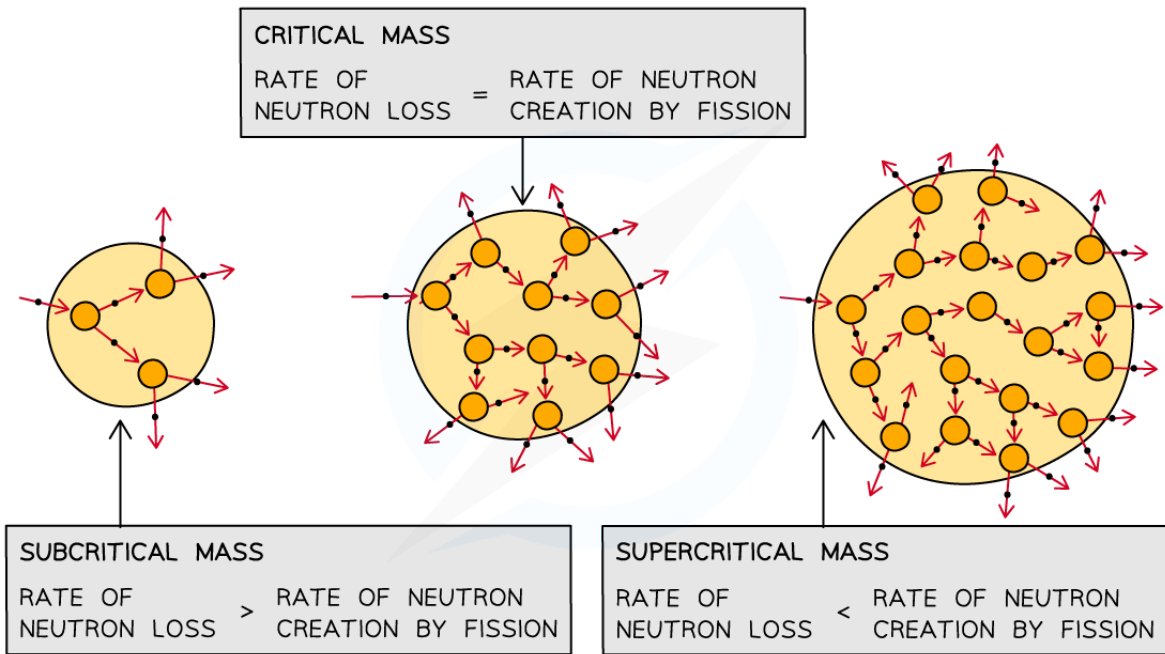
- Nuclear reactions are designed to be self-sustaining yet very controlled
- This can be achieved by using a precise amount of uranium fuel, known as the **critical mass**
- The critical mass is defined as:

**The minimum mass of fuel required to maintain a steady chain reaction**

- Using exactly the critical mass of fuel will mean that a single fission reaction follows the last
  - Using **less** than the critical mass (**subcritical mass**) would lead the reaction to eventually stop
  - Using **more** than the critical mass (**supercritical mass**) would lead to a runaway reaction and eventually an explosion



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**Subcritical, critical and supercritical mass**

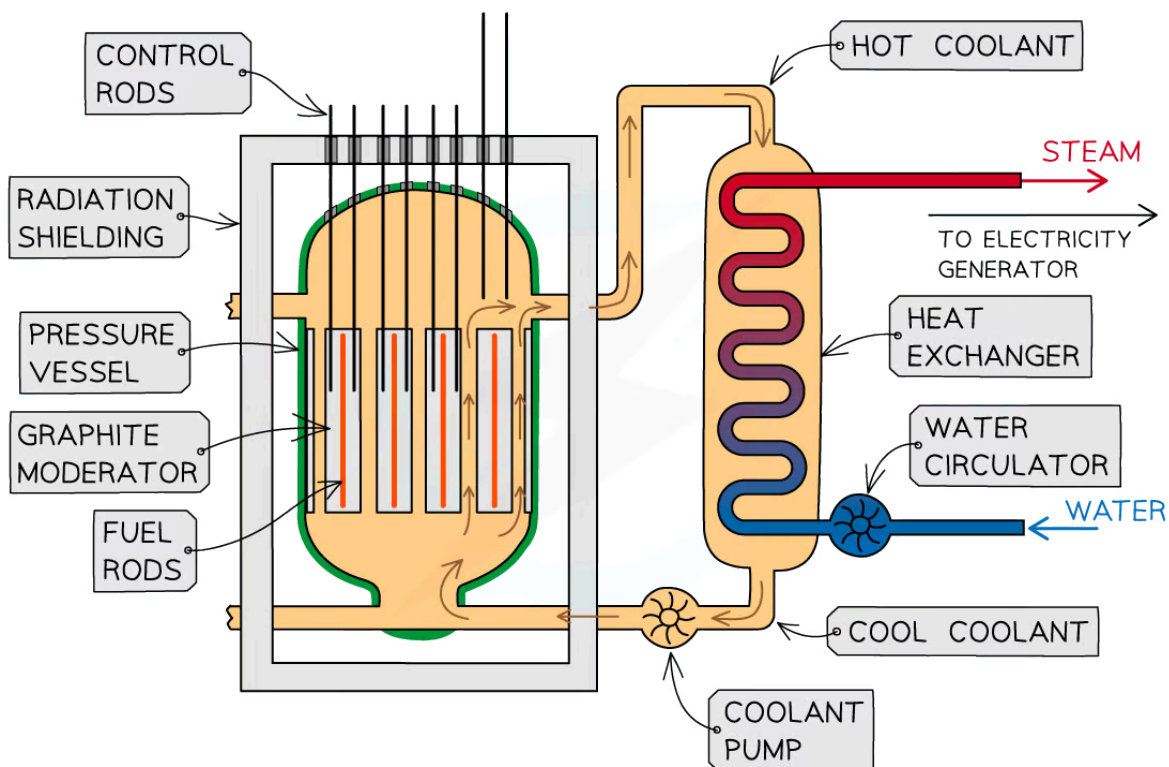


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## Operation of a Nuclear Reactor

### Operation of a Nuclear Reactor

- In a nuclear reactor, a chain reaction is required to keep the reactor running
- When the reactor is producing energy at the required rate, two factors must be controlled:
  - The **number** of free neutrons in the reactor
  - The **energy** of the free neutrons
- The main components of a nuclear reactor are:
  - Control rods
  - Moderators
  - Heat exchangers
  - Shielding



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*The overall purpose of a nuclear reactor is to collect the heat energy produced from nuclear reactions*

### Control Rods

**Purpose of a control rod:** To absorb neutrons

- Control rods are made of a material which **absorbs neutrons** without becoming dangerously unstable themselves



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- The number of neutrons absorbed is controlled by varying the depth of the control rods in the fuel rods
  - Lowering the rods further **decreases** the rate of fission, as more neutrons are absorbed
  - Raising the rods **increases** the rate of fission, as fewer neutrons are absorbed
- This is adjusted automatically so that exactly one fission neutron produced by each fission event goes on to cause another fission
- In the event the nuclear reactor needs to shut down, the control rods can be lowered all the way so no reaction can take place

## Moderator

**The purpose of a moderator:** To slow down neutrons

- The moderator is a material that surrounds the **fuel rods** and **control rods** inside the reactor core
  - Moderators are made from materials that are **poor absorbers** of neutrons, such as water
- The fast-moving neutrons produced by the fission reactions **slow down** by colliding with the molecules of the moderator, causing them to lose some momentum
- The neutrons are slowed down so that they are in **thermal equilibrium** with the moderator, hence the term 'thermal neutron'
  - This ensures neutrons can react efficiently with the uranium fuel

## Heat exchangers

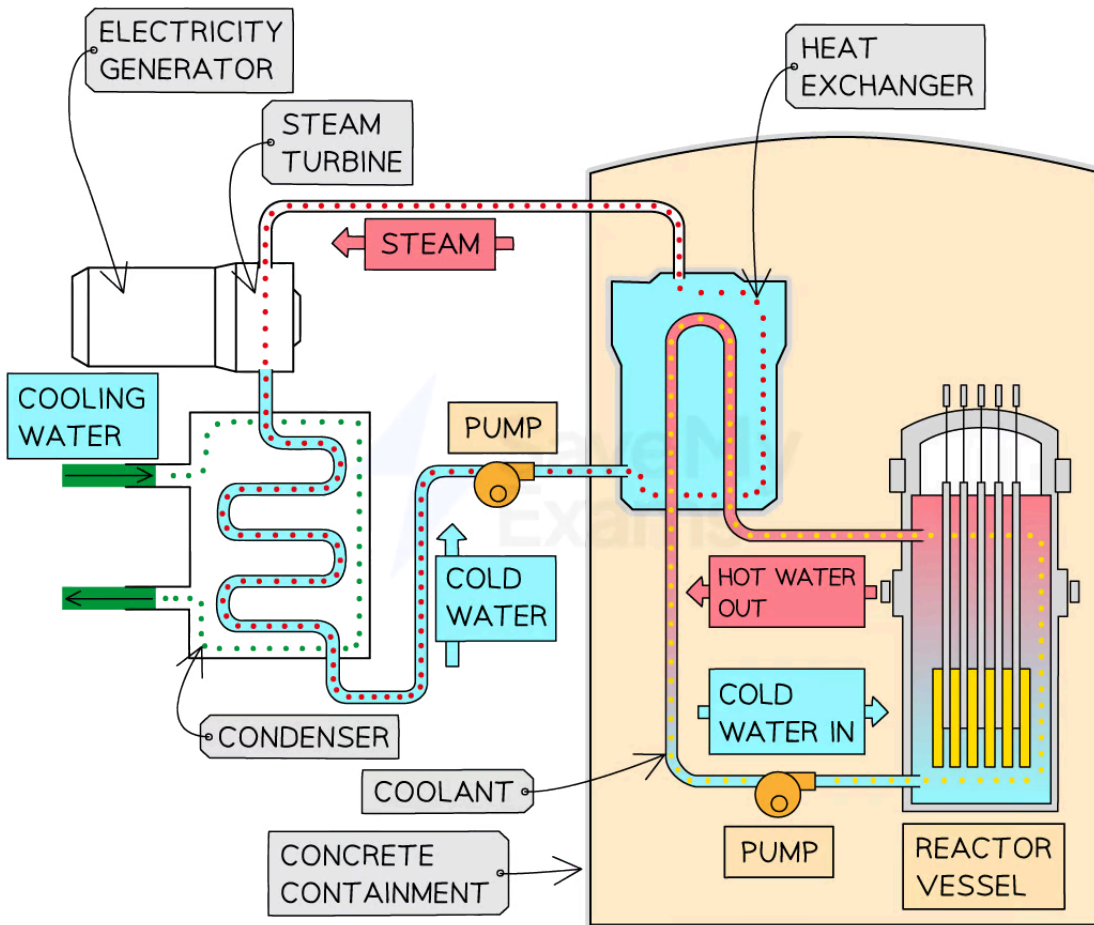
**The purpose of a heat exchanger:** To transfer thermal energy efficiently between the water systems of a nuclear power plant

- There are multiple water systems in a nuclear power plant that need regulating
  - The coolant (usually water) used in the reactor vessel
  - The water and steam that drives the turbine
  - The condenser that cools the steam
- The heat exchanger mediates the thermal energy exchanges between these water systems
- The **coolant** is a substance, such as water, that is pumped into the reactor at a cold temperature to extract the heat released by the fission reactions
- In the heat exchanger, the coolant transfers the heat to water that is pumped in externally to produce steam
- This steam then goes on to power electricity-generating turbines





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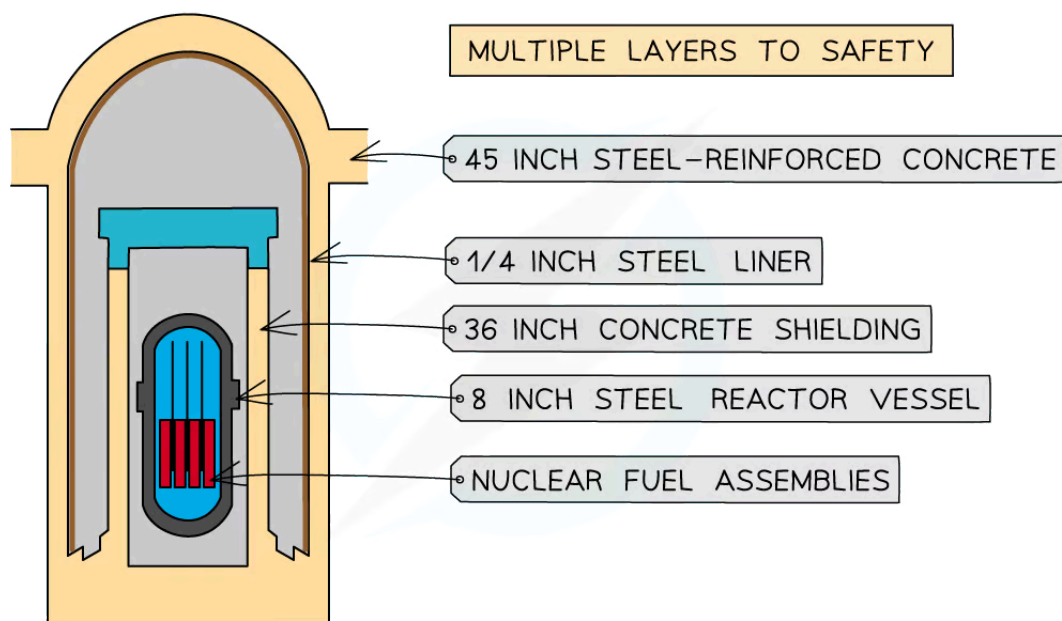
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*Water systems in a nuclear power plant are regulated by a heat exchanger*

## Shielding

**Purpose:** To house the reactor and absorb hazardous radiation

- The entire nuclear reactor is surrounded by **shielding** materials
- The daughter nuclei formed during fission, and the neutrons emitted, are radioactive
- The reactor is surrounded by a **steel** and **concrete** wall that can be nearly 2 metres thick
- This absorbs the emissions from the reactions
  - It ensures that the environment around the reactor is **safe**



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*Shielding metals in a nuclear reactor*



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## Radioactive Waste Management

### Safety Issues in Nuclear Power

#### Types of Radioactive Waste

- There are three main types of nuclear waste:
  - Low level
  - Intermediate level
  - High level

#### Low-level waste

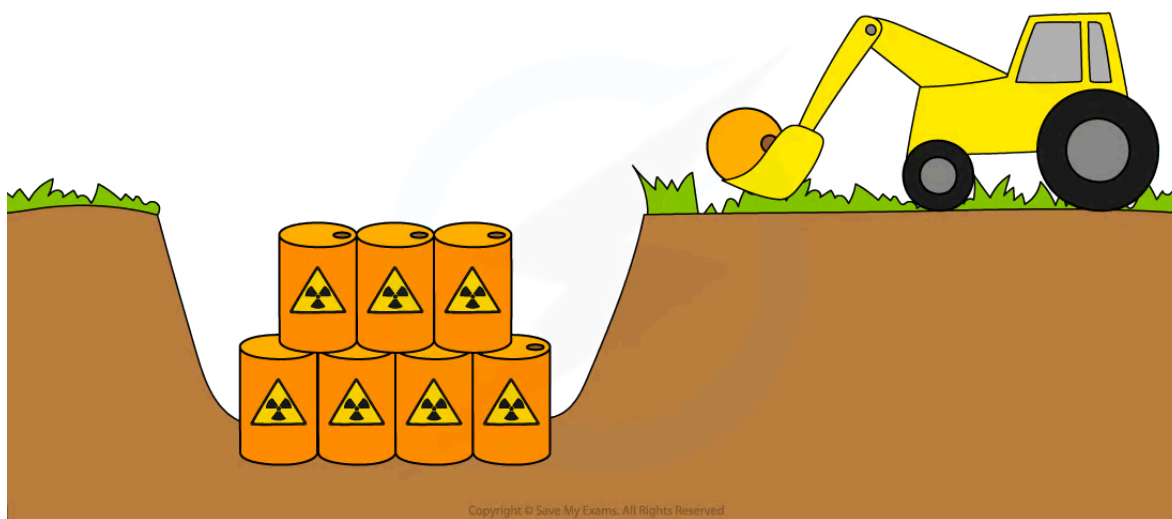
- This is waste such as clothing, gloves and tools which may be lightly contaminated
- This type of waste will be radioactive for a few years, so must be encased in concrete and stored a few metres underground until it can be disposed of with regular waste

#### Intermediate-level waste

- This is everything between daily used items and the fuel rods themselves
- Usually, this is the waste produced when a nuclear power station is decommissioned and taken apart
- This waste will have a longer half-life than the low-level waste, so must be encased in cement in steel drums and stored securely underground

#### High-level waste

- High-level waste refers to the unusable fission products from the fission of uranium-235 or from spent fuel rods
- This is by far the **most dangerous** type of waste as it will remain radioactive for thousands of years
- As well as being highly radioactive, the spent fuel rods are **extremely hot** and must be handled and stored much more carefully than the other types of waste
- The **issues** with high-level waste are:
  - Within the fuel rods, nuclei of **uranium-238** quickly decay into nuclei of **plutonium-239**
  - Plutonium-239 is classified as **high-level radioactive waste**
  - This is because its nuclei are extremely radioactive and have a **very long half-life** of 24 000 years
  - This presents a long-term risk of **contamination**
- The **treatment** of high-level waste is as follows:
  - The waste is initially placed in cooling ponds of water close to the reactor for a number of years
  - Isotopes of plutonium and uranium are harvested to be used again
  - Waste is mixed with molten glass and made solid (this is known as **vitrification**)
  - Then it is encased in containers made from steel, lead, or concrete
  - This type of waste must be stored very **deep** underground



*Depending on the activity of radioactive waste, it is buried in different ways*

## Advantages & Disadvantages of Nuclear Power

### Advantages of using nuclear power:

- **Climate change friendly:** Nuclear power stations produce **no greenhouse gases**
- **High energy density:** Uranium provides far **more energy per kg** compared to coal and other fossil fuels
- **Availability of fuel:** The reserves of fissionable materials are much higher compared to fossil fuel reserves
- **High reliability & safety:** Despite some serious incidents in the past, nuclear power is now regarded as one of the safest and most reliable processes for the production of electricity

### Disadvantages of using nuclear power:

- **Hazardous waste products:** The production of radioactive waste is very dangerous and expensive to deal with and stays at hazardous levels of activity for a very long time (>1000s of years)
- **Potential for catastrophic accidents:** A nuclear meltdown, such as at Chernobyl, could have catastrophic consequences on the environment and for the people living in the surrounding area
- **Potential for misuse:** There is a danger of misuse of nuclear material and infrastructure in nuclear weapons and terrorist attacks
- **Dangers with mining fuel:** There are many issues associated with mining uranium, from the people

handling it to the detrimental effects it can have on the environment



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## Environmental Considerations

- Isotopes with long half-lives must not enter our water and food supplies
- Burial locations must be geologically stable, secure from attack, and designed for safety
- Space for such locations is limited

## Safety Measures for Workers

- Several measures must be put in place to reduce the worker's exposure to radiation
- The fuel rods are **handled remotely** i.e. by machines
- The nuclear reactor is surrounded by a very thick lead or concrete **shielding** to limit exposure to radiation
- In an emergency, the control rods are fully lowered into the reactor core to stop fission reactions by absorbing all the free neutrons in the core, this is known as an **emergency shut-down**

## Nuclear Energy in Society

- Nuclear power can scare people if they do not understand it
- It is dangerous if not handled properly, yet it is invisible which can be difficult for some people to comprehend
- However, with increased education on nuclear energy, society can use this knowledge to inform their own decisions and opinions