Physics Factsheet

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Nuclear Reactors

This Factsheet explains the process by which energy is released by nuclear fission and how this energy is harnessed by a nuclear reactor.

Nuclear Fission

Nuclear fission is the splitting of an unstable, larger nucleus into two smaller nuclei. In a nuclear reactor the larger nucleus, which is usually an isotope of uranium, is unstable because it has too many neutrons. The uranium has been made unstable as it has been forced to absorb an additional neutron. The uranium nucleus has become unstable and split after absorbing a neutron. This is called **neutron-induced fission**.

An example of a fission reaction would be:

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

This nuclear transformation equation shows the uranium nuclei and the neutron on the left hand side of the arrow. These are the reactants. In this example, barium and krypton have been produced along with 3 additional neutrons. These products are shown on the right hand side of the arrow.

Note how the total of the atomic number (the number written as subscript) on both sides of the equation is the same, 92 + 0 = 92 and 56 + 36 + 0 = 92 on the right hand side. The atomic number represents the number of protons in each nucleus. No protons have been created or destroyed so the total number of protons remains the same.

Also, the total of the nucleon numbers (the number written as superscript) on both sides of the equation is the same, 235 +1 = 236 on the left hand side and 141 + 92 + (3×1) = 236 on the right hand side. The nucleon number represents the total number of protons plus neutrons in each nucleus. No protons or neutrons are destroyed during fission so the total number of protons plus neutrons remains the same.

> ***Nuclear Fission***
> *Nuclear fission is the splitting of a large, unstable nucleus into two, smaller, more stable nuclei. Neutron-induced fission is the fission of a large nucleus that has become unstable due to the absorption of an additional neutron.*

> ***Nuclear Transformation Equations.***
> *In any nuclear transformation equation, such as the example shown above for the fission of uranium, the total nucleon number and the total atomic number on both sides of the equation must be the same.*

How is energy released from nuclear fission?

When the total mass of all of the products in a fission reaction is calculated, it is less than the total mass of all of the reactants. In other words the products have a smaller mass than the reactants. The reaction produces a loss of mass called a **mass defect**. This mass defect has occurred due to a release of energy by the reaction, according to the equation:

> $E = mc^2$ where E = *energy released (J)*
> m = *mass defect (kg)*
> c = *speed of light in a vacuum* = 3.0×10^8 ms^{-1}.

This energy is released in the form of heat energy. This means that the product nuclei and neutrons move away from the reaction with incredible speeds as they have a lot of kinetic energy.

> Consider the masses of the nuclei from the fission example given above:
> Mass of uranium nucleus = 235.04 atomic mass units
> Mass of a neutron = 1.01 atomic mass units.
>
> So the total mass of reactants = 235.04 + 1.01
> = 236.05 atomic mass units.
>
> Mass of barium nucleus = 140.91 atomic mass units
> Mass of krypton nucleus = 91.91 atomic mass units
> Mass of 3 neutrons = 3 × 1.01 = 3.03 atomic mass units.
>
> So the total mass of products = 140.91 + 91.91 + 3.03
> = 235.85 atomic mass units.
>
> Mass defect = mass of products – mass of reactants
> = 236.05 – 235.85 = 0.20 atomic mass units
>
> Now, one atomic mass unit is equal to 1.6605×10^{-27} kg. This means that the mass defect from our fission example is:
>
> Mass defect = $0.20 \times 1.6605 = 0.3321 \times 10^{-27}$ kg
>
> The energy released from this fission can now be calculated:
>
> Energy released,
> E = mass defect × c^2
> $E = (0.3321 \times 10^{-27}) \times (3 \times 10^8)^2 = 2.99 \times 10^{-11}$ J
>
> This amount of energy may not seem like a huge amount but you must remember that this is for one reaction only and in a nuclear reactor there will be a huge number of reactions occurring in a short space of time, leading to a huge amount of energy being released.

> ***Energy Release From Fission***
> *When fission of a large nucleus occurs the products have a smaller mass than the reactants. This apparent loss of mass or mass defect is released as heat energy, giving the reactants large amounts of kinetic energy.*
>
> *The amount of energy released is related to the mass defect by the equation:*
>
> $E = mc^2$ *where:* E = *energy released (J)*
> m = *mass defect (kg)*
> c = *speed of light in a vacuum* = $3.0 x 10^8$ *m/s.*

> ***Exam Hint:*** *When doing this sort of calculation, check you are using the correct units - kg for mass, not atomic mass units*

Typical Exam Question
The nuclear transformation equation below represents the fission of uranium.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{146}_{57}La + ^{87}_{X}Br + 3^{1}_{0}n$$

(a) What is the missing atomic number of bromine? [1]
(b) Given the following masses of the nuclei involved in the fission, calculate the mass defect, in kg, caused by the fission. [4]

Mass of bromine nucleus = 86.92u
Mass of neutron = 1.01u
Mass of lanthanum nucleus = 145.90u
Mass of uranium nucleus = 235.04u
1u = 1.6605 × 10^{-27} kg

(c) Calculate the energy released in joules from one fission of uranium through this transformation. [2]

Answers
(a) In a fission reaction the total atomic number must be equal before and after the fission. Before the fission the total atomic number is 92+0 = 92. The total number after the fission must also be 92.
Missing nucleon number = 92 – 57 = 35 ✓

(b) The mass defect is found by calculating the difference between the masses of all of the products and all of the reactants. To turn the mass defect into kilograms the conversion factor that is given in the question is used.
Mass of reactants = uranium mass + neutron mass
= 235.04 + 1.01 = 236.05u ✓

mass of products = bromine mass + lanthanum mass + mass neutrons
= 86.92 + 145.90 +3(1.01) = 235.85 u ✓

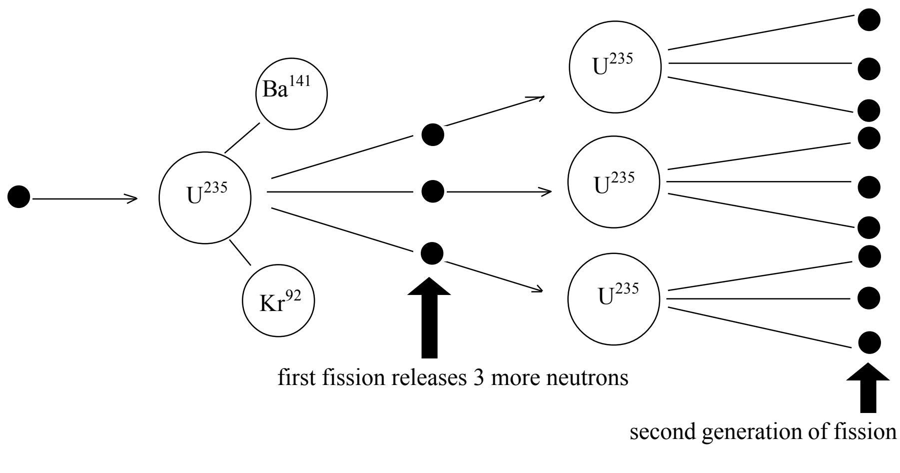
Mass defect = mass of reactants – mass of products
= 236.05 – 235.85 = 0.20 u ✓

Mass defect $= (0.20)(1.6605 \times 10^{-27}) = 3.21 \times 10^{-28}$ *kg* ✓

(c) The energy released is calculated by using $E = mc^2$ ✓
$E = mc^2 = (3.21 \times 10^{-28})(3 \times 10^8)^2 = 2.89 \times 10^{-11}$ *J* ✓

Chain Reactions
It has already been explained that when a neutron-induced fission occurs a heavy unstable nucleus splits into two smaller nuclei. Usually, the fission of a uranium nucleus also produces two or three additional neutrons. Each one of these additional neutrons is now able to collide with a nearby uranium nucleus and cause a further fission. In turn each of these fission reactions will liberate further neutrons that are able to cause further fission reactions. The process can be self-sustaining by forming a **chain reaction**.

The diagram below represents the first few stages in a chain reaction:



One fission may release 3 neutrons. These 3 neutrons will go on to cause 3 further fissions releasing 9 neutrons. These 9 neutrons will go on to cause 9 fissions releasing 27 neutrons, etc, etc.

Each time a fission reaction occurs there is a mass defect and a release of energy. The process of fission takes a very short time, about 0.001 seconds. This means that within a very short space of time there are a huge number of fission reactions taking place, releasing a fantastic amount of energy.

Self Sustaining Chain Reactions
Not all of the neutrons that are produced by a fission reaction will go on to cause further fission of other uranium nuclei. Some neutrons will escape the uranium into the surroundings.

If, on average, one neutron from each fission reaction goes on to cause a further fission then the chain reaction will be just self-sustaining at a steady rate and the reaction is called critical.

If, on average, more than one neutron from each fission reaction goes on to cause a further fission then the chain reaction will very quickly spiral out of control and become explosive. This type of reaction is called super-critical and forms the basis of an atomic bomb!

If, on average, less than one neutron from each fission reaction goes on to cause a further fission then the chain reaction will die out.

The number of neutrons that escape the uranium and do not cause further fission reactions is dependent on two factors:

(i) The mass of uranium. A smaller mass has a larger surface area in proportion to its volume and so there is a greater chance of a neutron escaping the uranium with a smaller mass. The mass of a material required to produce a self sustaining critical reaction is called the **critical mass.**

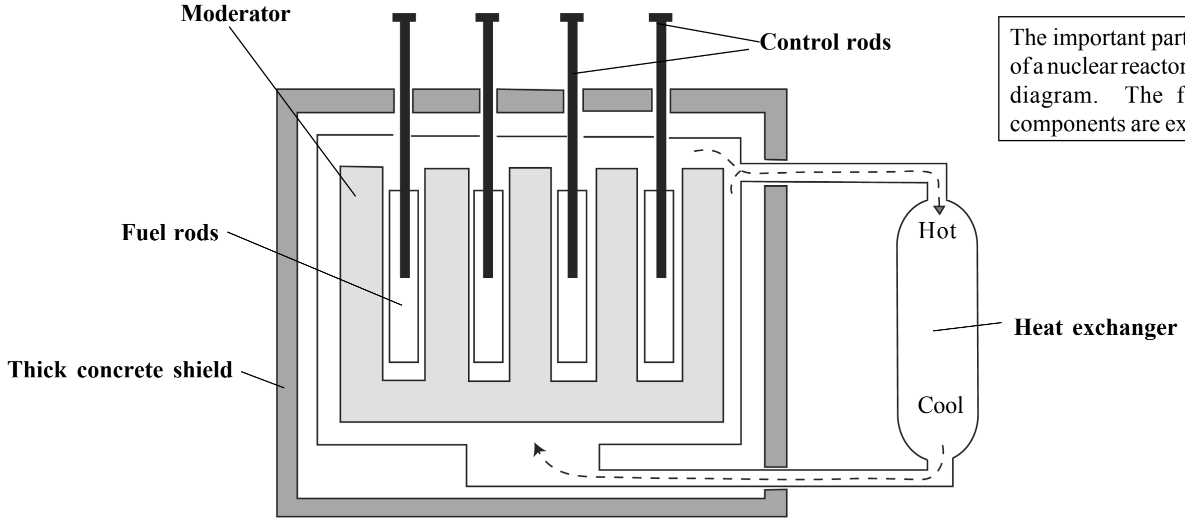
(ii) The shape of the uranium. A long thin piece of uranium will allow a lot of neutrons to escape but a sphere will keep more neutrons inside the uranium for longer, giving them more chance to cause further fission reactions. This means that the critical mass of a material depends on the shape of the material.

The critical mass for uranium is about 15kg if the uranium is in the shape of a sphere. This is a sphere with a radius of about 6cm or the size of a grapefruit. Slightly more uranium in the sphere would produce a super critical chain reaction.

Critical Mass
The critical mass is the mass of material required to create a chain reaction that is self sustaining at a steady rate. This is called a critical chain reaction and is created when one neutron, on average, from every fission goes on to cause a further fission of a nucleus.

Nuclear Fission Reactors

The diagram below represents a simplified design of a gas cooled nuclear reactor:



The important parts and components of a nuclear reactor are labelled on the diagram. The function of these components are explained below

Moderator - In naturally occurring uranium only about 1 atom in 140 is a uranium 235 ($^{235}_{92}U$)isotope. The rest of the atoms are uranium 238 ($^{238}_{92}U$).

Uranium 235 requires comparatively slower moving neutrons to cause fission. Uranium 238 requires comparatively faster moving neutrons to cause fission.

The average speed of naturally occurring neutrons from a fission reaction is usually somewhere in between these two speeds. Therefore, in a nuclear reactor a moderator is used. This slows neutrons down to a speed that is more likely to cause fission in uranium 235 nuclei.

The neutrons collide with the nuclei of the moderator and transfer kinetic energy to the nuclei. Neutrons that have been slowed down by a moderator are called ***thermal neutrons***. Most reactors use graphite or water as the moderator.

Control Rods - These are able to absorb neutrons from the reactor. Neutrons that are absorbed by the control rods do not go on to cause further fission reactions. The control rods can be moved in and out of the fuel to absorb more or less neutrons. In this way the reactor can support a self-sustaining reaction at a steady rate where only one neutron from each fission reaction goes on to cause a further fission reaction.

If the nuclear reactor is producing too much energy and is in danger of becoming super-critical the control rods are lowered further into the reactor and they absorb more neutrons. If the reactor is not producing enough energy and is in danger of dying out then the control rods are lifted further out of the reactor and less neutrons are absorbed.

Cadmium and boron are good materials to use as control rods as they are very good at absorbing neutrons.

Coolant - The coolant that is labelled in the diagram above is a gas; carbon dioxide is usually used, but water is also commonly used. The coolant passes through the reactor and becomes hot. The hot coolant then passes through a heat exchanger. Inside the heat exchanger the coolant transfers its heat to steam. The steam is then used to turn a turbine and drive a generator. The coolant continually circulates around the reactor core, taking away the heat energy that is produced so that it can be converted into electrical energy.

Fuel Rods - The most commonly used fuel is 'enriched uranium'. This is uranium that has had the proportion of uranium 235 isotope increased to around 3%. The fuel rods are long and thin to facilitate the easy escape of neutrons into the moderator. The moderator slows the neutrons down before they return to the fuel rod and cause another fission reaction.

Thick Concrete Shield - This acts as a barrier to stop any neutrons escaping from the reactor core. The thickness of the concrete is typically as much as 5 metres. This thickness of concrete will stop any neutrons, beta particles and gamma photons, which are all produced in the core, from escaping. Neutrinos can also be produced inside the core and these will pass through the concrete but they are not harmful.

Choice of Moderator

The choice of material to use as a moderator is crucial in a nuclear reactor. An effective moderator must slow down the neutrons quickly without absorbing them. The kinetic energy of the neutron is reduced through collisions with the nuclei of the moderator. If the moderator nuclei are too heavy, the neutrons will simply bounce off and lose little kinetic energy. If the moderator nuclei are stationary and equal to the mass of the neutron then the neutron will become stationary after the collision. An effective moderator should therefore nave nuclei that are moving and have about the same mass as a neutron.

Candidate 1 – Hydrogen Gas : Although the nuclei (single protons) are moving and have the same mass as a neutron it is impractical to use a gas as a moderator inside the reactor core.

Candidate 2 – The hydrogen nuclei within water molecules : The hydrogen nuclei are moving and have the same mass as the neutrons. Unfortunately hydrogen nuclei are prone to absorbing neutrons to become the hydrogen isotope – deuterium.

Candidate 3 – The deuterium nuclei within 'heavy water' molecules: Water molecules can also be formed that use deuterium atoms instead of hydrogen atoms. These nuclei are only twice as heavy as the neutrons and they are moving. The draw back is that 'heavy water' is inconvenient and expensive to produce in a pure form.

Candidate 4 – Carbon Graphite: Carbon nuclei have about 12 times the mass of a single neutron and so they are less effective at slowing neutrons down. The neutrons have to undergo many collisions with the carbon graphite nuclei before they are slow enough to cause fission in a uranium 235 nucleus. Despite this drawback the carbon graphite is cheap and easily obtained. It is for this reason that carbon graphite is used in nuclear reactors as the moderator.

Characteristics of an effective moderator material

An effective moderator material must slow down a fast moving neutron to a speed that is capable of causing fission in a uranium 235 nucleus through as few a collisions as possible with the nuclei of the moderator material. This means that an effective moderator nucleus should be moving and have about the same mass as a neutron.

Typical Exam Question
The *control rods*, the *coolant* and the *thick shield* surrounding the reactor core are essential parts of a fission nuclear reactor.
For each of these components:
(i) explain its function
(ii) suggest one suitable material
(iii) give one essential physical property that the material must have. [12]

Answers
Control Rods
(i) *Control rods control the rate of reaction so that the chain reaction is just self sustaining or critical.*✓
The control rods do this by absorbing neutrons from the reactor core so that, on average, one neutron from each fission reaction goes on to cause a further fission. To achieve a critical reaction the control rods can be lowered and raised into the reactor core to absorb more or less neutrons when required.✓
(ii) *Cadmium is a suitable material.* ✓
(iii) *The control rod material must be a good absorber of neutrons.*✓

Coolant
(i) *The coolant transfers heat energy away from the reactor core.*✓
The coolant is taken to a heat exchanger where it is used to heat up steam that will eventually turn a turbine and drive an electricity generator.✓
(ii) *Water, or carbon dioxide gas.*✓
(iii) *The coolant must have a high heat capacity to transfer as much heat energy as possible.* ✓

Thick shield surrounding core
(i) *The thick shield prevents harmful radiation from escaping the reactor core.*✓
The shield absorbs neutrons, beta particles and gamma photons that are produced inside the core. ✓
(ii) *Concrete is a suitable material.*✓
(iii) *The thick shield must be a good absorber of radiation.*✓

Qualitative (Concept) Test
1. What is nuclear fission?
2. Why is energy released during the nuclear fission process and in what form is the energy released?
3. (a) With reference to the neutrons involved in the nuclear fission process, under what circumstances would a chain reaction be just self sustaining?
   (b) Under what circumstances would a chain reaction become 'super-critical?
4. What two physical factors affect the critical mass of material that can undergo neutron-induced fission? Explain how each factor effects the critical mass.
5. In a nuclear reactor what are the functions of the following components:
   (a) The moderator
   (b) The coolant
   (c) The control rods
6. What are the characteristics needed by a good moderator, and why?

Quantitative (Calculation) Test
1. When $^{235}_{92}U$ is bombarded by neutrons, two possible fission products are $^{95}_{39}Y$ and $^{139}_{53}I$.
   (a) Give a nuclear transformation equation for this process.
   (b) Given the following masses of the nuclei involved in the fission, calculate the mass defect of the fission.
   Mass of uranium 235 = 235.04u Mass of yttrium 95 = 94.91u
   Mass of iodine 139 = 138.91u Mass of one neutron = 1.01u
   $1u = 1.6605 \times 10^{-27}$ kg
   (c) What is the energy, in joules, that is released during one of the fission reactions?

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Exam Workshop
This is a typical poor student's answer to an exam question. The comments explain what is wrong with the answers and how they can be improved. The examiner's mark scheme is given below.

Natural Uranium consists of 99.3% $^{238}_{92}U$ **and 0.7%** $^{235}_{92}U$**. In many nuclear reactors, the fuel consists of enriched uranium.**

(a) (i) Explain what is meant by enriched uranium. [1]
Uranium with more fuel in it. *0/1*

This answer needs to be more specific. The fuel of a nuclear reactor is uranium 235. The proportion of uranium 235 is around about 3% in enriched uranium.

(ii) Why is enriched uranium used rather than natural uranium in nuclear reactors? [2]
There is more fuel in enriched uranium. *0/2*

Again, it is specifics that are lacking in this answer. No mention has been made of fission and how fission of uranium 235 is the source of energy release in the reactor.

(b) (i) Explain how the rate of heat production is controlled in a nuclear reactor. Your answer should refer to the thermal neutrons involved in the fission process. [3]
The heat given out by the reactor increases if the control rods are removed as there are more neutrons. When the control rods are inserted into the reactor there are fewer neutrons and the heat given out decreases. *1/3*

This answer is insufficiently detailed for this number of marks - the candidate should include more information about the role of neutrons in fission as is indicated in the question.

(ii) Explain why the nuclear fuel in a nuclear reactor is shaped as many long thin rods. [4]
The neutrons must leave the fuel so that they can be slowed down *1/4*

Again, what the candidate has mentioned is correct but there needs to be more detail in a question with this many marks.

Examiner's answers
(a) (i) *The quantity of uranium 235 is greater in enriched uranium than in naturally occurring uranium.*✓
(ii) *The fission reactions occur in uranium 235 and so the amount of available fuel is greater in enriched uranium.*✓
(b) (i) *Each fission reaction releases 2 or 3 neutrons.*✓
Only one neutron from every fission reaction is required to cause a further fission reaction.✓
The control rods absorb any neutrons that are not needed to ensure that the chain reaction remains at a steady rate.✓
(ii) *The neutrons must be slowed down by the moderator.*✓
The neutrons must therefore escape the fuel rods.✓
Neutrons can more easily escape a long thin rod than any other shape.✓
Also, the long thin fuel rods are more easily replaced, in stages, than a larger piece of fuel.✓

Quantitative Test Answers
1. (a) $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{139}_{53}I + ^{95}_{39}Y + 2^{1}_{0}n$ ✓✓
   (b) Mass of reactants = uranium mass + neutron mass
   = 235.04 + 1.01 = 236.05u✓
   Mass of products = yttrium mass + iodine mass + mass neutrons
   = 94.91 + 138.91 +2(1.01) = 235.84 u✓
   Mass defect = mass of products – mass of reactants
   = 236.05 – 235.84 = 0.21 u✓
   Mass defect = $(0.21)(1.6605 \times 10^{-27}) = 3.49 \times 10^{-28}$ kg ✓
   (c) The energy released is calculated by using $E = mc^2$.
   $E = mc^2 = (3.49 \times 10^{-28})(3 \times 10^8)^2 = 3.141 \times 10^{-11}$ J ✓✓