IB · HL · Physics

3 hours 15 questions

Structured Questions

Fission

Spontaneous & Induced Fission / Energy Released in Fission Reactions / Chain Reactions from Fission / Operation of a Nuclear Reactor / Radioactive Waste Management

Easy (5 questions)	/59
Medium (5 questions)	/52
Hard (5 questions)	/57
Total Marks	**/168**

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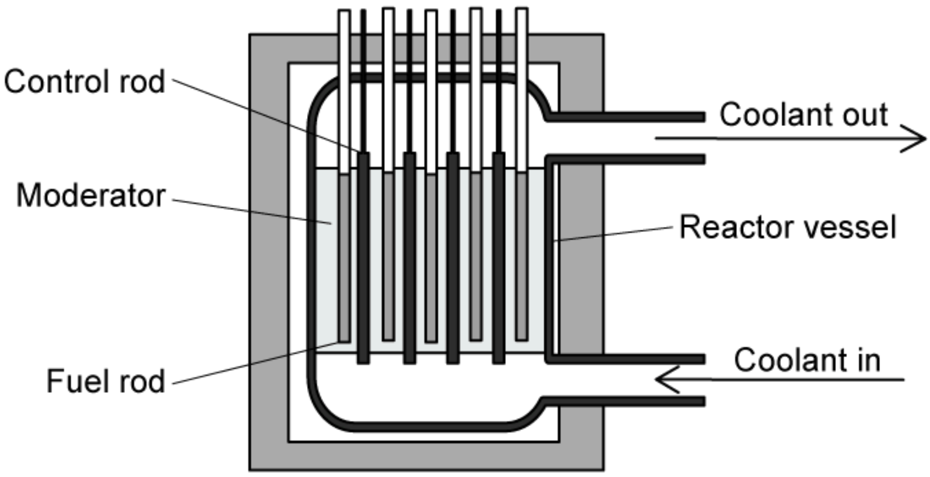
Easy Questions

1 (a) Outline the difference between spontaneous and induced fission.

(3 marks)

(b) Induced fission occurs in nuclear reactors.

The structure of a nuclear reactor is shown in the diagram.



(i) State the material used in the fuel rods.

[1]

(ii) Outline the function of the control rods and the moderator.

[2]

(3 marks)

(c) Explain how a chain reaction can occur in the reactor by completing the following sentences:

Nuclear fission can be induced by firing .... at a nucleus.

When the nucleus is struck it splits into smaller .... nuclei plus two or three .... are released which go on to initiate further fission reactions.

....

....

....

(3 marks)

(d) Explain what happens to the energy released by fission in a nuclear reactor.

....

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(2 marks)

2 (a) Nuclear reactors generate power from the fission of uranium-235.

There are key components to all nuclear reactors which allow the rate of fission reactions to be controlled.

Draw line to match the component of a nuclear reactor to its purpose.

Component
Coolant
Control rods
Moderator
Shielding

Purpose
absorbs excess neutrons
ensures no harmful radiation leaks outside the reactor
transports heat
slows neutrons to thermal speeds

(4 marks)

(b) Outline the effect on the rate of fission inside a nuclear reactor when excess neutrons are removed and explain why this happens.

(2 marks)

(c) During fission, the fast-moving neutrons which are released must be slowed to become thermal neutrons.

(i) Outline what is meant by *thermal neutron*.

[1]

(ii) Explain why neutrons must be slowed.

[1]

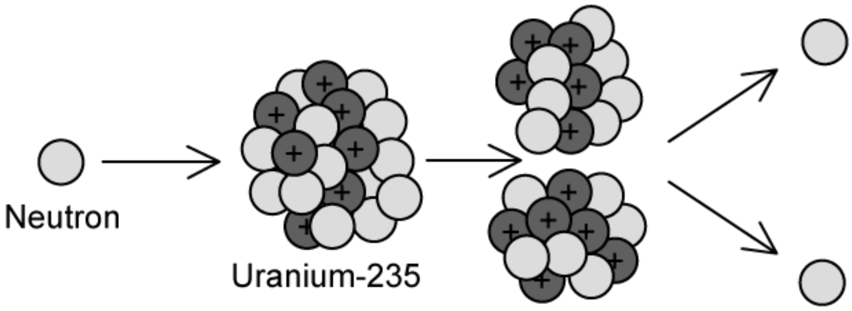
(2 marks)

(d) State the property a material must have to be used as a moderator in a nuclear reactor.

....

(1 mark)

3 (a) A neutron is fired at a uranium-235 nucleus causing it to produce two smaller nuclei and two neutrons.



State the name of the process shown in the diagram.

....

(1 mark)

(b) Explain the difference between radioactive decay and the process shown in (a).

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(4 marks)

(c) Complete the following sentences:

A self-sustaining and controlled chain reaction can be maintained in the core of a nuclear reactor when the number of neutrons .... in a given time is .... the number of neutrons .... in a given time.

This can be achieved by using a precise amount of uranium fuel, known as the ....

....

....

....

(3 marks)

(d) Complete the flow diagram below which shows the sequence of energy transfers that take place in a nuclear power station

nuclear energy in fuel

⇓

.... of fission products

⇓

.... of water and steam

⇓

kinetic energy of ....

⇓

.... of turbines

⇓

electrical energy

....

....

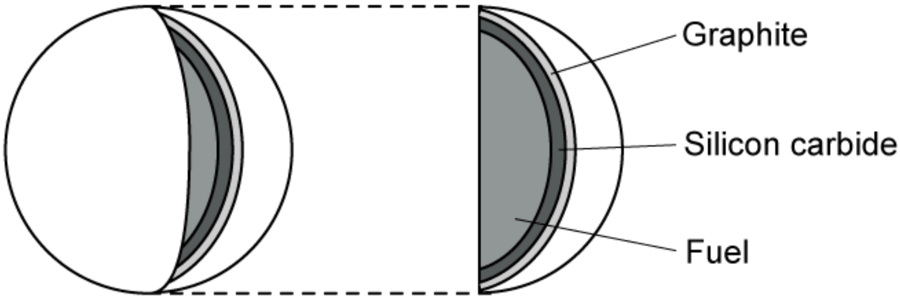
....

....

(4 marks)

4 (a) Nuclear fuel is contained inside spheres with a silicon carbide layer which is designed to contain the remaining fission fragments for at least one million years.

The diagram shows one of the fuel spheres that make up a fuel rod found in a nuclear reactor.



Section through a fuel sphere

Explain what is meant by the term **fission fragments** and give an example.

....

....

(2 marks)

(b) (i) Outline whether spent fuel rods would be classified as low-level, mid-level, or high-level nuclear waste.

[1]

(ii) Explain why it is important to store spent fuel rods away safely for such a long time.

[2]

....

....

....

(3 marks)

(c) Outline **two** methods for the long-term storage of nuclear waste.

....

(2 marks)

(d) Outline

(i) **two** advantages of using nuclear fuel over other energy sources

[2]

(ii) **two** disadvantages of using nuclear fuel over other energy sources

[2]

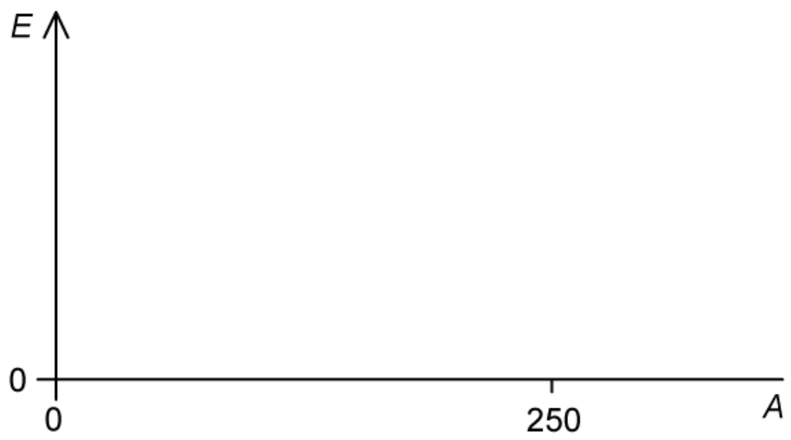
(4 marks)

5 (a) (i) State what is meant by nuclear fission.

[1]

(ii) On the axes below, sketch the variation with nucleon number *A* of the binding energy per nucleon *E* of a nucleus.

[2]



(iii) Explain, with reference to your graph, why nuclear fission reactions result in the release of energy.

[2]

(5 marks)

(b) The mass of a uranium-235 $\left({}^{235}_{92}\text{U}\right)$ nucleus is 235.043943u, the mass of a proton is 1.007276u, and the mass of a neutron is 1.008665u.

The unified atomic mass unit u is approximately equal to 1.661×10^{-27} kg.

For a nucleus of uranium−235, calculate

(i) the total mass of the separate nucleons, in terms of u.

[2]

(ii) the mass defect, in kg.

[2]

(4 marks)

(c) Calculate:

(i) the energy released, in J, if all of the mass in a nucleus of uranium−235 were converted into energy.

[2]

(ii) the binding energy of a uranium−235 nucleus in MeV per nucleon.

[2]

(4 marks)

(d) A nuclear fission reaction occurs that has the following equation

$$ {}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{90}_{38}\text{Sr} + {}^{143}_{54}\text{Xe} + x\,{}^{1}_{0}\text{n} $$

(i) Determine, for this nuclear reaction, the value of x.

[1]

(ii) The binding energy per nucleon of the fission products ${}^{90}_{38}\text{Sr}$ and ${}^{143}_{54}\text{Xe}$ are given in the table below.

Use the data to calculate the energy, in MeV, released in this reaction.

[2]

	binding energy per nucleon / MeV
$^{90}_{38}Sr$	8.70
$^{143}_{54}Xe$	8.20

....

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(3 marks)

Medium Questions

1 (a) A nuclear fission reaction occurs that has the following equation:

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{90}_{38}Sr + ^{143}_{54}Xe + 3^{1}_{0}n$$

Estimate the amount of energy released during the fission reaction using the following information:

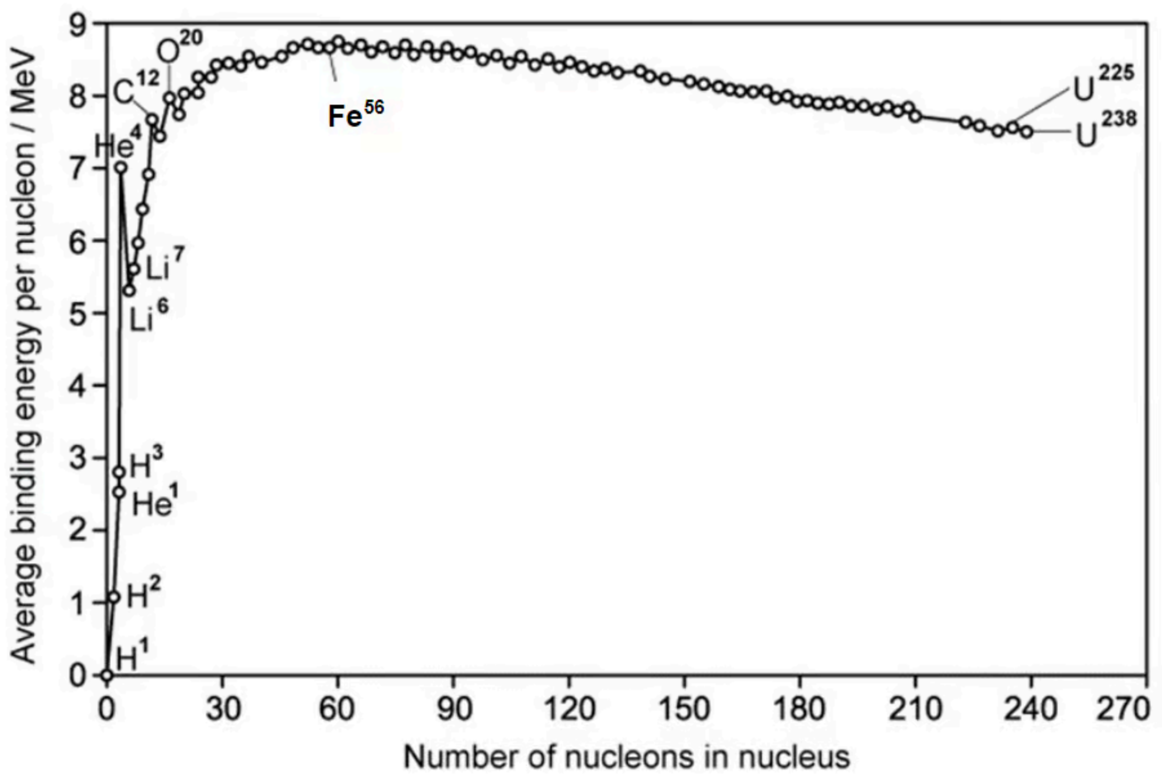
- Binding energy per nucleon of Uranium-235 = 7.59 MeV/nucleon
- Binding energy per nucleon of Strontium-90 = 8.70 MeV/nucleon
- Binding energy per nucleon of Xenon-143 = 8.20 MeV/nucleon

....

....

(2 marks)

(b) The binding energy per nucleon curve is shown:



With reference to the binding energy per nucleon curve:

(i) Explain why fission is possible.

[2]

(ii) Identify the source of energy released during this process.

[2]

(4 marks)

(c) A uranium-235 nucleus undergoes fission into two approximately equally sized products.

Use the data from the graph in **(b)** to show that the energy released as a result of the fission is approximately 4×10^{-11} J.

Use the graph to show how you have used the data.

(4 marks)

2 (a) When a uranium-235 nucleus absorbs a slow-moving neutron, it may undergo fission. One of the possible pairs of fission fragments are technetium-112 and indium-122, plus two neutrons are released.

The binding energy per nucleon of these nuclei are shown in the table below.

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

Show that the energy released in each fission of uranium-235 is about 200 MeV.

....

....

(2 marks)

(b) Under the right conditions, two hydrogen-2 nuclei can fuse to make a helium-4 nucleus.

Nucleus	Mass / u
^{2}H	2.0135
^{4}He	4.0026

Using the data in the table, show that the energy available as a result of the fusion of two hydrogen-2 nuclei is about 4×10^{-12} J.

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....

(4 marks)

(c) Compare the energy available from the complete fission of 1 kg of uranium-235 with the energy available from the fusion of 1 kg of hydrogen-2.

(3 marks)

(d) Fission and fusion reactions release different amounts of energy.

Discuss **other** reasons why it would be preferable to use fusion rather than fission for the production of electricity, assuming that fusion reactions could be produced on Earth as easily as fission reactions.

(2 marks)

3 (a) The core of a thermal nuclear reactor contains many components that are exposed to moving neutrons.

Outline what happens to a neutron that is incident on

(i) the moderator

[1]

(ii) a control rod.

[1]

....

....

(2 marks)

(b) A slow-moving neutron is fired at a nucleus and triggers a nuclear reaction.

Outline what happens in the process.

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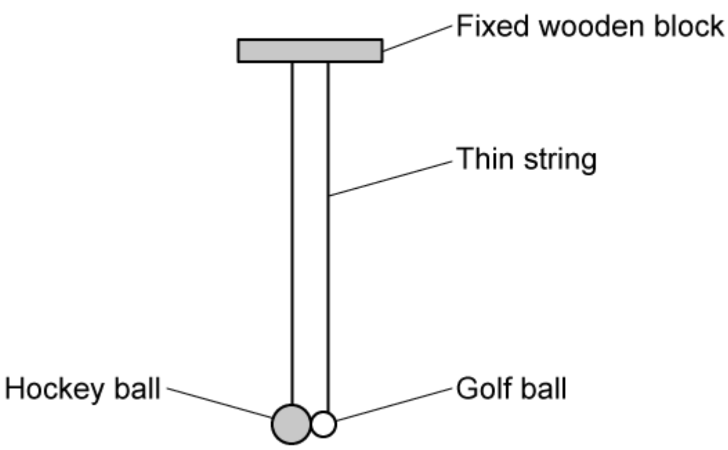
(3 marks)

(c) A teacher demonstrates the principle of moderation in a nuclear reactor by setting up the arrangement shown in the diagram.



In the arrangement, a golf ball initially hangs vertically and just touches a hockey ball which has three times the mass of the golf ball.

In the demonstration, the golf ball is pulled up to the side and released. After the collision, the balls move in opposite directions with equal speeds.

(i) Explain how this demonstration relates to the moderation process in a reactor.

[2]

(ii) State **two** ways in which the collisions in a nuclear reactor differ from the collision in the demonstration.

[2]

(4 marks)

(d) A thermal nuclear reactor produces radioactive waste.

Discuss some of the problems faced in the management of radioactive waste.

In your answer you should refer to:

- The main source of the most dangerous waste
- A brief outline of how waste is treated
- Problems faced in dealing with the waste, with suggestions for overcoming these problems.

(3 marks)

4 (a) In a thermal nuclear reactor, a chain reaction is maintained in the core that is operating normally.

Explain

(i) what is meant by a chain reaction, naming the materials and particles involved

[2]

(ii) the purpose of a moderator in a thermal nuclear reactor.

[2]

(4 marks)

(b) (i) Describe the changes made inside a nuclear reactor to reduce its power output and explain the process involved.

[2]

(ii) State the main source of the highly radioactive waste from a nuclear reactor.

[1]

(3 marks)

(c) Water is used in many thermal nuclear reactors as it has useful properties for acting as both a moderator and a coolant.

Describe the properties of water which make it useful as

(i) a moderator

[2]

(ii) a coolant in the heat exchanger.

[2]

(3 marks)

(d) Thermal nuclear reactors are usually fortified with layers of concrete.

Explain why concrete is a commonly used building material for nuclear reactors.

(2 marks)

5 (a) The majority of nuclear reactors use the isotope uranium-235 as fuel.

Each fission reaction of uranium-235 generates 180 MeV of energy.

Estimate the specific energy of uranium-235, in J kg^{-1}.

(2 marks)

(b) A nuclear power station generates a useful power output of 0.95 GW and has an overall efficiency of 43%.

Determine the mass of uranium-235 required per day to maintain this power output.

(2 marks)

(c) The specific energy of natural gas, a type of fossil fuel, is approximately 54 MJ kg^{-1}.

Using your answer to **(a)**, suggest an advantage of nuclear power compared with a natural gas power station.

(1 mark)

(d) Nuclear reactors tend to use enriched uranium as fuel.

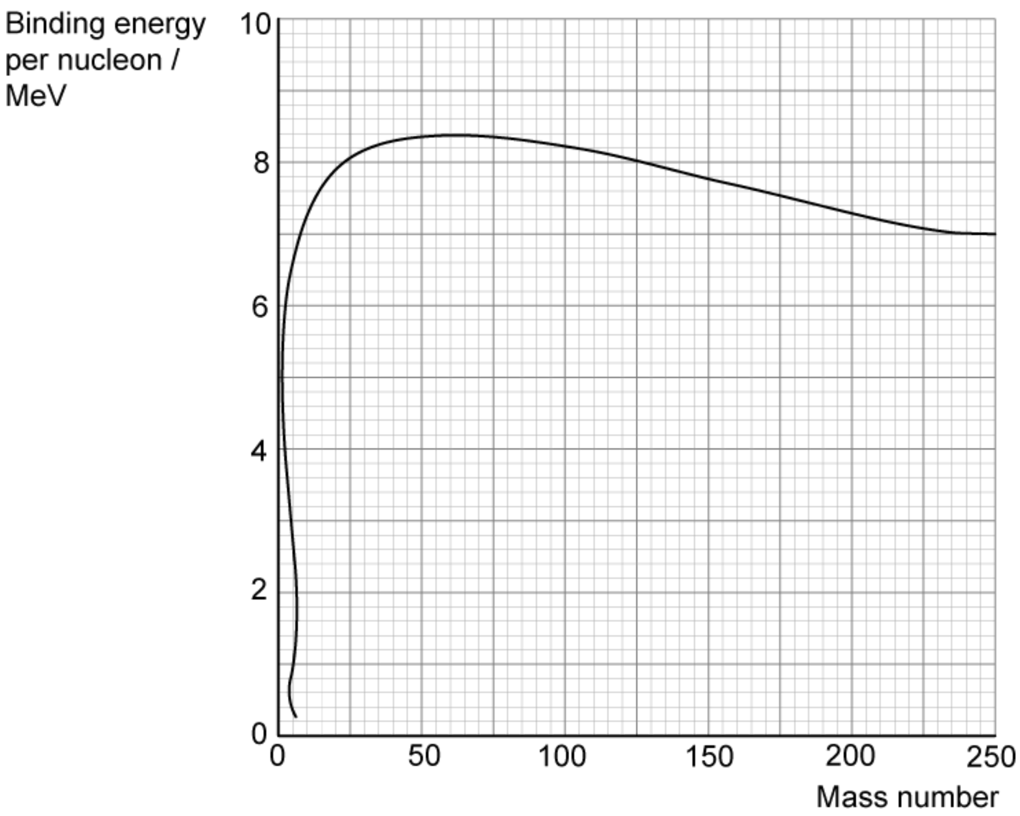
This is fuel in which the ratio of U-235 to U-238 has been artificially increased from that found in naturally occurring uranium ore.

For the same reactor as in **(b)**, estimate the total mass of enriched fuel required per year if it initially contains 3% uranium-235 and 97% uranium-238.

(2 marks)

Hard Questions

1 (a) The graph shows the relationship between the binding energy per nucleon and the mass number for various nuclides.



During the process of fission, nuclei of uranium-235 are bombarded by slow-moving neutrons. When a neutron is absorbed, a nucleus of uranium-236 is momentarily formed before splitting into two fission fragments, krypton-92 and barium-141, along with the release of other fission products.

Calculate the energy released during this fission process.

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(3 marks)

(b) Identify the other fission products in this process and justify why they can be discounted from the calculation in (a).

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(2 marks)

(c) A different fission process, involving uranium–235 is again triggered by the absorption of a slow–moving neutron and releases gamma ray photons. The process is described by the equation below:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{138}_{52}\mathrm{Te} + ^{98}_{40}\mathrm{Zr} + \gamma$$

In this process, 90% of the energy released is carried away as kinetic energy of the two daughter nuclei.

The following data are available:

- Mass of $^{235}_{92}\mathrm{U}$ = 235.0439u
- Mass of $^{138}_{52}\mathrm{Te}$ = 137.9603u
- Mass of $^{98}_{40}\mathrm{Zr}$ = 97.9197u
- Mass of $^{1}_{0}\mathrm{n}$ = 1.0087u
- Wavelength of γ photons emitted = 2.5×10^{-12} m

Show that approximately 32 gamma ray photons are released in this process.

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(4 marks)

(d) Assuming both nuclei are initially at rest, show that the $^{98}_{40}\mathrm{Zr}$ nucleus is emitted with a speed that is about 1.4 times greater than the speed of the $^{138}_{52}\mathrm{Te}$ nucleus.

(2 marks)

2 (a) One possible fission reaction of uranium-235 is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2^{1}_{0}n$$

The following data are available:

- Mass of one atom of $^{235}_{92}U$ = 235u
- Binding energy per nucleon for $^{235}_{92}U$ = 7.59 MeV
- Binding energy per nucleon for $^{140}_{54}Xe$ = 8.29 MeV
- Binding energy per nucleon for $^{94}_{38}Sr$ = 8.59 MeV

Calculate the amount of energy released in the reaction.

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(4 marks)

(b) A nuclear power station uses the uranium-235 as fuel. The useful power output of the power station is 1.4 GW and it has an efficiency of 30%.

(i) Show that the specific energy of $^{235}_{92}U$ is about 7.5×10^{13} J kg^{-1}.

[2]

(ii) Determine the mass of $^{235}_{92}U$ which undergoes fission in one day.

[2]

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(4 marks)

(c) Young people have swum for many years in an unusually warm Siberian river near to a secret nuclear reactor like the one described in **(b)**. It is alleged that this reactor makes regular discharges of nuclear waste into the river.

Explain why the water is unusually warm and evaluate the most significant health risk posed to young swimmers.

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(3 marks)

3 (a) In a nuclear reactor, the mean energy produced by each uranium-235 nucleus that undergoes induced fission is 3.0×10^{-11} J.

Oil releases approximately 50 MJ of heat per kg when it is burned in air.

Using a suitable calculation, discuss **one** advantage and **one** disadvantage of using nuclear fuel over fossil fuels, such as oil, to produce electricity.

Molar mass of uranium-235 = 0.235 kg mol^{-1}

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(4 marks)

(b) In a nuclear reactor, neutrons released by fission travel with very high energies. To increase the likelihood of further fission reactions, these neutrons need to be sufficiently slowed to be captured by other uranium-235 nuclei.

An ideal moderator slows neutrons without capturing them. The best moderating materials are light elements, which undergo elastic collisions with the high-energy neutrons.

Explain why lighter elements, such as hydrogen, tend to be more effective moderators than heavier elements.

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(2 marks)

(c) The first few collisions between a neutron and the nuclei in the moderator transfer sufficient energy to excite the nuclei to higher nuclear energy levels.

Describe and explain:

(i) the nature of the radiation that may be emitted from excited moderator nuclei.

[2]

(ii) what happens to the neutrons as a result of the repeated collisions with the moderator nuclei.

[2]

(4 marks)

(d) By considering the neutrons involved in a nuclear reactor, explain

(i) how the rate of production of heat is controlled

[2]

(ii) why the fuel is not placed in a single fuel rod.

[2]

(4 marks)

4 (a) Natural uranium consists of 99.3% $^{238}_{92}U$ and 0.7% $^{235}_{92}U$.

To be used as fuel in a nuclear reactor, natural uranium must be enriched and enclosed in sealed metal containers.

Explain why

(i) natural uranium is not suitable for use as nuclear fuel

[1]

(ii) enrichment is favoured over chemically separating the isotopes from each other.

[2]

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(3 marks)

(b) When a uranium–235 nucleus undergoes fission, one of the possible reactions is:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{139}_{54}Xe + ^{95}_{38}Sr + 2^{1}_{0}n \left(+ \text{energy}\right)$$

The binding energy per nucleon, *E*, is given in the table below:

Nuclide	E / MeV
$^{235}_{92}U$	7.60
$^{139}_{54}Xe$	8.39
$^{95}_{38}Sr$	8.74

A 1500 MW nuclear reactor, operating at 27% efficiency, uses enriched fuel containing 2% uranium–235 and 98% uranium–238. The molar mass of uranium−235 is 0.235 kg mol^{-1}.

Estimate the total mass of original fuel required per year in the nuclear reactor.

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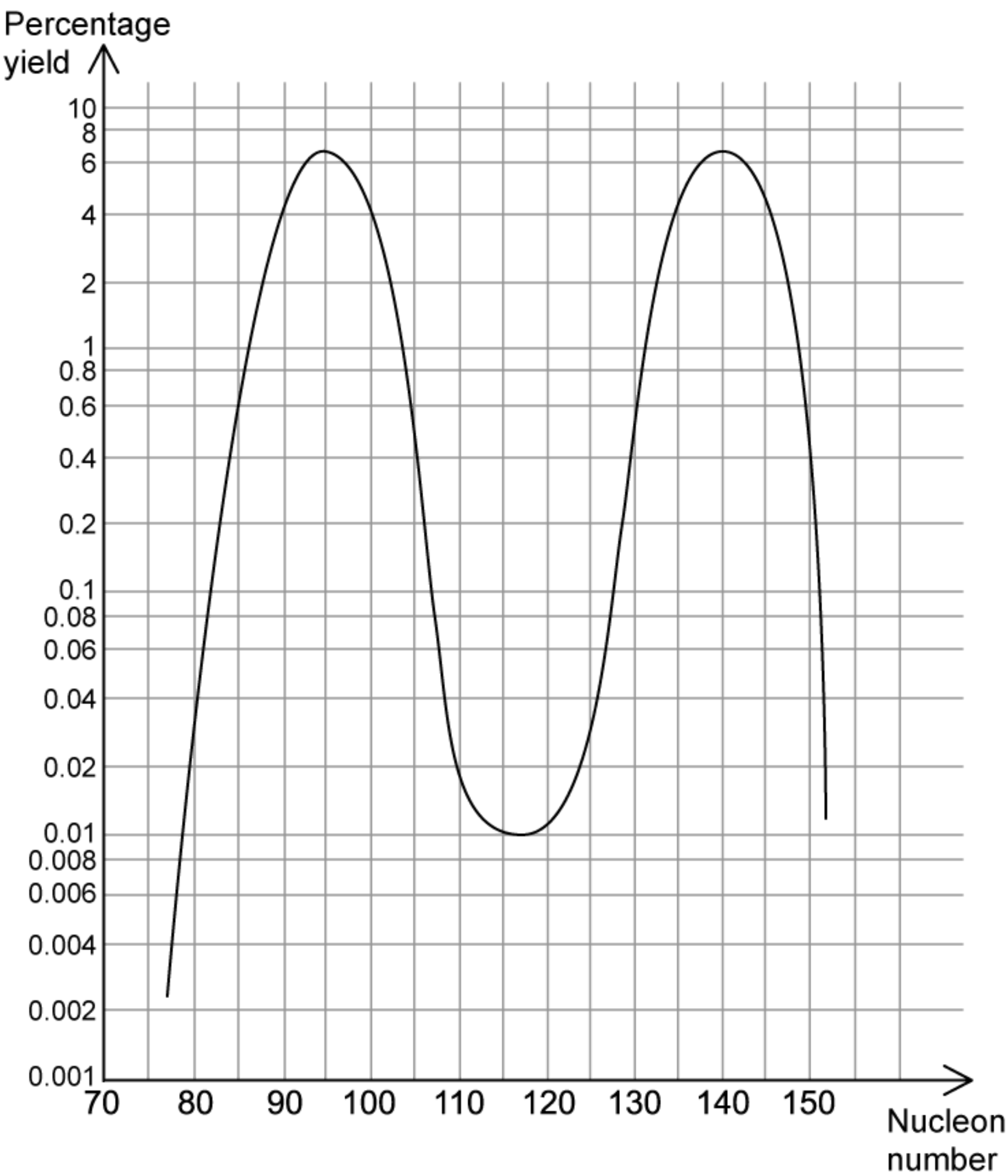
(5 marks)

(c) Determine the number of fission reactions per day in the nuclear reactor assuming the production of power is continuous.

(2 marks)

5 (a) The fission products from a large sample of fissioned uranium-235 are analysed. The percentage yield of each fission product is plotted against its nucleon number on the fission yield curve shown below.



The fission of uranium-235 can be described by the equation

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{a}_{b}X + ^{c}_{d}Y + Z^{1}_{0}n$$

The fission products X and Y may have equal masses, however, this is not true for every possible pair of fission products.

Using the fission yield curve

(i) Suggest the values of *a* and *c* that are most likely to be produced in the fission of uranium-235.

[2]

(ii) Show that these fission products are approximately 600 times more likely to be produced than two products of equal mass.

[2]

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(4 marks)

(b) One of the two fission products is a $^{147}_{56}\text{Ba}$ nucleus.

The second product $^{a}_{b}\text{X}$ is known to be one of the elements shown in the table.

element	proton number
Br	35
Kr	36
Rb	37
Sr	38
Y	39
Zr	40

Other data for this reaction:

- Mass of $^{235}_{92}\text{U}$ = 235.043923u
- Mass of $\left(^{147}_{56}\text{Ba} + {}^{a}_{b}\text{X}\right)$ = 232.844603u

For this reaction:

(i) Identify the second fission product $^{a}_{b}\text{X}$ and determine the percentage yield of the two products.

[2]

(ii) Calculate the energy released per fission of uranium-235, in MeV.

[2]

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(4 marks)

(c) The products of uranium-235 fission are often radioactive and follow decay series until they form a stable nuclide.

Two examples of fission products with their decay series and half-lives are shown below.

$$^{99}_{42}\text{Mo} \xrightarrow{67\ \text{hr}} {}^{99}_{43}\text{Tc} \xrightarrow{200\ 000\ \text{yr}} {}^{99}_{44}\text{Ru}\ \text{(stable)}$$

$$^{140}_{54}\text{Xe} \xrightarrow{16\ \text{s}} {}^{140}_{55}\text{Cs} \xrightarrow{1.1\ \text{min}} {}^{140}_{56}\text{Ba} \xrightarrow{13\ \text{days}} {}^{140}_{57}\text{La} \xrightarrow{40\ \text{hr}} {}^{140}_{58}\text{Ce}\ \text{(stable)}$$

Discuss the problems associated with the short and long-term storage of these fission fragments and suggest potential solutions for overcoming them.

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(3 marks)