7 Read the passage below and answer the questions that follow.

Research into nuclear fusion as a power source for generating electricity began in the 1940s, but it has only recently been possible to achieve fusion ignition. Fusion ignition occurs when there is a greater output of energy from the fusion reaction process than the input of energy required to maintain the process.

There are several different nuclei that can be used as the fuel in the fusion process. The most promising ones are the isotopes of hydrogen, deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$). The fusion of deuterium and tritium occurs at a lower temperature than other nuclei and also releases more energy than other fusion reactions. The reaction equation is shown.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

The binding energies per nucleon of the nuclei in the equation are given in Table 7.1.

Table 7.1

nucleus	binding energy per nucleon / MeV
$^{2}_{1}H$	1.112
$^{3}_{1}H$	2.827
$^{4}_{2}He$	7.074

Deuterium is relatively common. About 1 out of every 5000 hydrogen atoms in sea water is in the form of deuterium. However, naturally occurring tritium is extremely rare on Earth. There are only trace amounts, formed by the interaction of cosmic rays with the atmosphere. Tritium can be produced artificially by bombarding atoms of lithium ($^{6}_{3}Li$) with neutrons. The resulting nucleus splits into a helium nucleus and a tritium nucleus.

There are currently two main types of fusion reactor in the research stage.

One of these types of reactor uses magnetic confinement. Examples are the JET fusion reactor in the UK and the European ITER experiment. Strong magnetic fields in the region of 6–12 T are used to confine the fuel which is in the plasma state. The temperatures are so high in the plasma state that the atoms have been stripped of all their electrons. The deuterium and tritium nuclei each need to have a mean kinetic energy of approximately 105 keV. When operating, the JET reactor requires an input of energy greater than can be supplied from the national network. The required extra energy of 3.75 GJ is stored in a rotating flywheel of mass 775 000 kg with a maximum speed of rotation of 225 revolutions per minute.

The other main type of reactor uses inertial confinement by high-power laser beams. This is used in the NIF experiment in the USA. The laser beams initially have a low power but are amplified many times, travelling a total distance of 1500 m in order to reach the required energy of 2.05 MJ. The surface of a small sphere of fuel of diameter 2.0 mm is heated by 192 of these laser beams. Some of the fuel becomes a plasma, which explodes away from the surface. The remaining fuel is compressed by the explosion into a small volume of extremely high density so that its temperature increases. When the temperature and density are high enough, fusion reactions occur. In December 2022, NIF recorded the first experiment where fusion ignition occurred. An output energy of 3.15 MJ was achieved for an input of 2.05 MJ of laser energy. This reaction produced 4.8×10^{17} neutrons and used 2.0% of the available fuel in the small sphere.

Nuclear fusion is often referred to as a clean energy source. However, as with fission reactors, when a fusion reactor is decommissioned, there will be radioactive materials to be disposed of from the reaction container.

(a) State what is meant by isotopes of hydrogen.

....

.... [1]

(b) **(i)** On Fig. 7.1, sketch the variation of binding energy per nucleon with nucleon number for all isotopes.

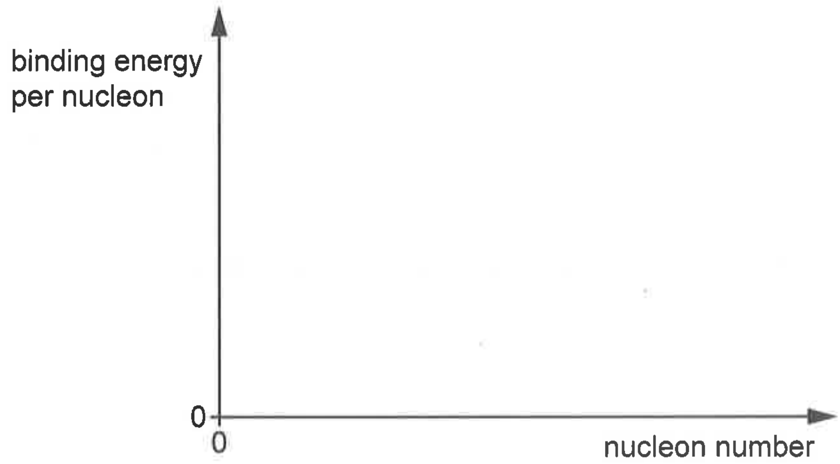

Fig. 7.1

[2]

(ii) Explain why the nuclei used as the fuel in fusion reactors must have nucleon numbers smaller than that of iron.

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.... [1]

(c) **(i)** Calculate the energy released, in MeV, when one deuterium nucleus fuses with one tritium nucleus.

energy = ...MeV [2]

(ii) In one fusion reaction, the neutron and the helium nucleus that are produced have a total momentum of zero.

Explain why the neutron has more kinetic energy after the fusion reaction than the helium nucleus.

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.... [3]

(d) State the nuclear equation for the formation of tritium from lithium.

[2]

(e) Explain how the magnetic field used to confine the fuel in the JET and ITER experiments changes the direction of motion of the deuterium and tritium nuclei.

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.... [2]

(f) (i) Assuming that the plasma in a magnetic confinement reactor behaves as an ideal gas, calculate the temperature T required for the fusion of deuterium and tritium.

T = ... K [2]

(ii) Suggest why temperatures such as those in **(f)(i)** are often quoted without specifying K or °C.

....

.... [1]

(g) The energy E stored in a rotating flywheel of radius r is given by:

$$E = \frac{mr^2\omega^2}{4}$$

where m is the mass of the flywheel and ω is the angular velocity of the flywheel.

Calculate the radius of the rotating flywheel in the JET reactor.

radius = ... m [3]

(h) The fusion reaction at NIF uses inertial confinement.

(i) Explain what is meant by inertia.

....

....

.... [1]

(ii) Calculate the time it takes for the laser beam to travel the total distance to the sphere of fuel.

time = ... s [1]

(iii) Calculate the total mass of the fuel in the sphere.

Assume that the fuel contains an equal number of deuterium nuclei and tritium nuclei.

mass = ... kg [2]

(iv) Suggest why fusion reactions result in the production of radioactive nuclei in the material of the container.

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.... [1]

[Total: 24]