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

Ionizing radiation affects DNA molecules within cells, which are critical in cell reproduction. It has its greatest effect on cells that rapidly reproduce, including most types of cancer. It can induce cancer and cure cancer. It is used routinely for medical diagnostic purposes.

The biological effects of ionizing radiation on living tissue are directly proportional to the amount of ionization produced in the living tissue. The amount of ionization produced is in turn proportional to the energy deposited.

Absorbed dose of a radiation refers to the amount of ionizing radiation energy absorbed per unit mass of tissue. The unit for absorbed dose is the **gray (Gy)**, which is defined to be

$$1 \text{ Gy} = 1 \text{ J kg}^{-1}.$$

The biological effects of ionizing radiation also depend on the type of radiation and the type of tissue. **Dose equivalent** of a radiation considers both the amount of radiation absorbed and the medical effects of that type of radiation. It is calculated by multiplying the absorbed dose in grays by a quality factor called the **relative biological effectiveness (RBE)**, and is measured in **sievert (Sv).**

$$1 \text{ Sv} = 1 \text{ Gy} \times \text{RBE}$$

Table 8.1 gives the RBE values for several types of ionizing radiation.

Type and energy of radiation	**RBE**
X-rays	1
γ rays	1
β rays (> 32 keV)	1
β rays (< 32 keV)	1.7
neutrons, thermal to slow (< 20 keV)	*5
neutrons, fast (1 - 10 MeV)	10 (body), 32 (eyes)
protons (1 - 10 MeV)	10 (body), 32 (eyes)
α rays from radioactive decay	*20
heavy ions from accelerators	*20

*only maximum values provided

Table 8.1

The greater the dose equivalent, the greater the biological effects. If a radiation exposure is spread out over a longer duration, greater doses are needed to cause the same biological effect. This is due to the body's ability to partially repair the damage.

Laws regulate radiation doses to which people can be exposed. The greatest occupational whole-body dose that is allowed is about 20 to 50 mSv in a year and is rarely reached by medical and nuclear power plant workers.

(a) **(i)** With reference to Table 8.1 and the characteristics of the different ionising radiations, explain the following:

1. α rays have a higher RBE than X-rays, γ rays and energetic β rays.

…………………………………………………………………………………………

…………………………………………………………………………………………

…………………………………………………………………………………………

…………………………………………………………………………………………[2]

2. Neutrons do not carry any electrical charge but have an RBE greater than 1.

…………………………………………………………………………………………

…………………………………………………………………………………………[1]

(ii) To limit or reduce radiation doses, one general principle is to *limit the time of exposure*. Suggest two other general principles to limit radiation doses.

……………………………………………………………………………………………

……………………………………………………………………………………………[2]

(iii) Calculate the dose absorbed over a period of one year by the lung tissue of a weapons plant employee who inhales and retains plutonium-239 in an accident. The activity of the plutonium-239 inhaled remains approximately constant at 3.70×10^4 Bq over many years.

The mass of the affected lung tissue is 2.00 kg, and each plutonium-239 nucleus decays by emitting a 5.23 MeV α-particle.

dose = ………………………….. Sv [3]

(b) A *radioactive tracer* is a drug that contains radioactive isotopes. It can be injected into a patient. Gamma emitters make good radioactive tracers.

Once the tissues and organs have absorbed the tracer, radiation from the tracer is captured by a special camera outside the body that produces images, allowing doctors to diagnose the condition of the patient.

(i) In addition to being safer since gamma radiation has a lower RBE, suggest one other advantage of using a gamma-emitting tracer in a patient, rather than a beta-emitting tracer.

…………………………………………………………………………………………………

…………………………………………………………………………………………………

…………………………………………………………………………………………………[1]

(ii) Biological half-life is the time taken by the human body to eliminate, by natural excretion, half of the amount of a substance (such as a radioactive material) that has entered the body. The process is approximately exponential.

The effective decrease of radioactivity of a tracer in the body is due to both the physical decay of the tracer and the biologic elimination of the tracer by the body.

The effective decay constant λ_E of the tracer is given by

$$\lambda_E = \lambda_B + \lambda_T$$

where λ_T is the nuclear decay constant of the radioisotope in the tracer,
and λ_B is the biological decay constant of the tracer.

Show that the effective half-life t_E of the tracer is given by

$$t_E = \frac{t_T t_B}{t_T + t_B}$$

where t_T is the nuclear half-life of the radioisotope in the tracer,
and t_B is the biological half-life of the tracer.

[1]

(iii) A patient is given an injection containing 1.0×10^{-12} g of technetium-99m, which has a nuclear half-life of 6.02 hours. The molar mass of technetium-99m is 99 g.

1. Show that the initial activity of the technetium-99m is 1.9×10^{5} Bq.

activity = ………………………….. Bq [2]

2. Calculate the effective half-life of the technetium-99m if its biological half-life in the body is 24 hours.

effective half-life = ………………………….. h [1]

3. Determine the activity of the technetium-99m remaining in the patient 3.0 days after the injection.

activity = ………………………….. Bq [2]

(c) It is often convenient to represent the decay of a radioactive sample with time using a semi-log graph as it produces a straight-line plot.

When a sample contains a mixture of unrelated radioactive nuclides (i.e. no parent-daughter relationships), the total activity A_{total} of the sample is just the sum of the individual activities of the different nuclides.

$$A_{total} = A_1 + A_2 + \dots$$

where A_1 is the activity due to the first nuclide,
and A_2 is the activity due to the second nuclide, and so on.

In this case, the plot of A_{total} against time will be a curve on the semi-log graph.

Fig.8.1 shows the total activity curve A_{total} for a sample consisting of two unrelated radioactive nuclides. The dashed line A_1 is the activity curve for nuclide 1, which has the longer half-life. Nuclide 2 has an activity of 5 Bq on day 18, indicated by point P.

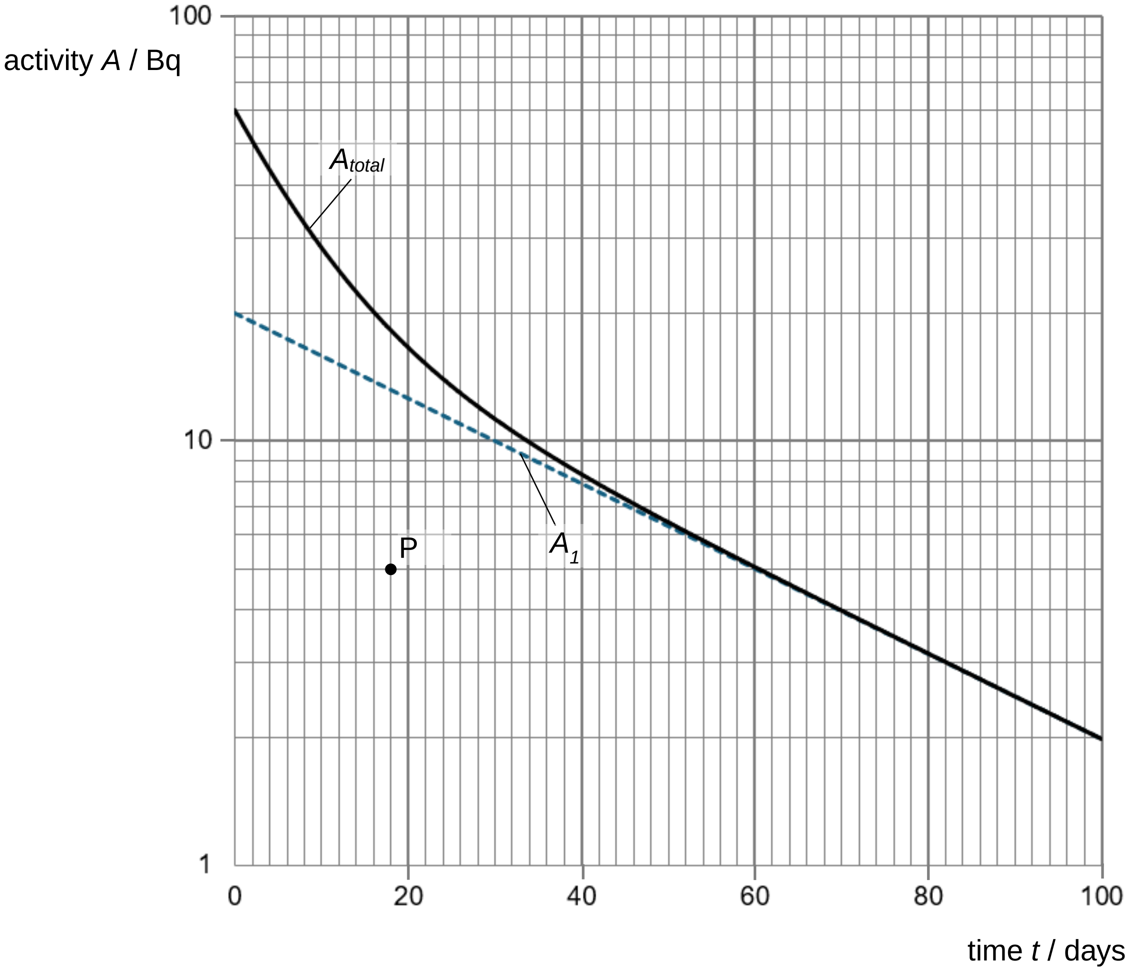

Fig. 8.1

(i) Explain why the slope of the graph of A_{total} against time will eventually follow the slope of the line for the activity of the radioactive nuclide having the longer half-life.

……………………………………………………………………………………………………….

……………………………………………………………………………………………………[1]

(ii) State the half-life of nuclide 1.

half-life = ………………………….. day [1]

(iii) Determine the initial activity of nuclide 2 at t = 0 day.

activity = ………………………….. Bq [1]

(iv) Draw a line in Fig.8.1 to show the variation with time t of the activity of nuclide 2. Label this line A_2. [1]

(v) Hence or otherwise, determine the half-life of nuclide 2.

half-life = ………………………….. day [1]

[Total: 20]