8 Read the passage and answer the questions that follow.

In 2021, the American space agency NASA landed an exploration vehicle called Perseverance on the surface of Mars. Perseverance was designed to undertake a series of experiments. Perseverance and all of its experiments are powered by a radioisotope thermoelectric generator (RTG).

RTGs are used as power supplies for devices that are remote and unmanned, for example space probes and satellites. RTGs can only produce a power output of a few hundred watts, so they are only useful for low-power applications. The energy released through radioactive decay is used to generate thermal energy. The thermal energy is converted into electrical energy by using thermocouples.

A thermocouple consists of two junctions between two different metals. The junctions are at different temperatures, as shown in Fig. 8.1.

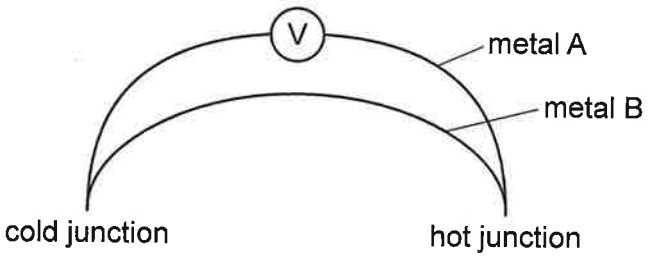

Fig. 8.1

The radioactive decay of the radioisotope produces thermal energy that maintains the temperature of the hot junction. The temperature difference ΔT between the hot and cold junctions of the thermocouple causes the thermocouple to generate an electromotive force (e.m.f.).

The e.m.f. generated depends on ΔT and the two metals used. Each metal has a property called the Seebeck coefficient. The e.m.f. is proportional to the difference in Seebeck coefficients ΔS between the two metals. The e.m.f. is given by

$$\text{e.m.f.} = \Delta S \Delta T.$$

The radioisotope used needs a long half-life. Perseverance uses plutonium-238, which has a half-life of 87.7 years and is an alpha emitter. The plutonium is in the form of plutonium dioxide, which has a molar mass of $276\,\text{g mol}^{-1}$. Plutonium-238 is part of a radioactive decay series that ends with a stable isotope of lead ($^{206}_{82}\text{Pb}$).

Data for Perseverance is shown in Table 8.1.

Table 8.1

lifespan of Perseverance / years	14
total mass of Perseverance / kg	1025
mass of plutonium dioxide / kg	4.9
electrical power output of RTG at launch / W	110
hot junction temperature / K	1273
cold junction temperature / K	573
Seebeck coefficients of the two thermocouple metals / $\mu\text{V K}^{-1}$	–200, 240

The radioisotope is encased in a high-strength container. This is to prevent any fragments of plutonium from being absorbed by living organisms while the RTG is still on Earth.

The plutonium generates thermal energy in the RTG at a rate of a few kilowatts. However, the electrical power output of the RTG is much less than this. This power output decreases exponentially by 0.79% each year.

Carbon dioxide is very abundant on Mars. One of the experiments performed by Perseverance is MOXIE, a process to separate oxygen from carbon dioxide. The molar mass of oxygen is $32\,g\,mol^{-1}$. The first time MOXIE was used, it produced 5.37 g of oxygen. The process of operating MOXIE included both a warm-up time and an oxygen production time, as shown in Fig. 8.2. This whole process required a continuous power supply of 300 W.

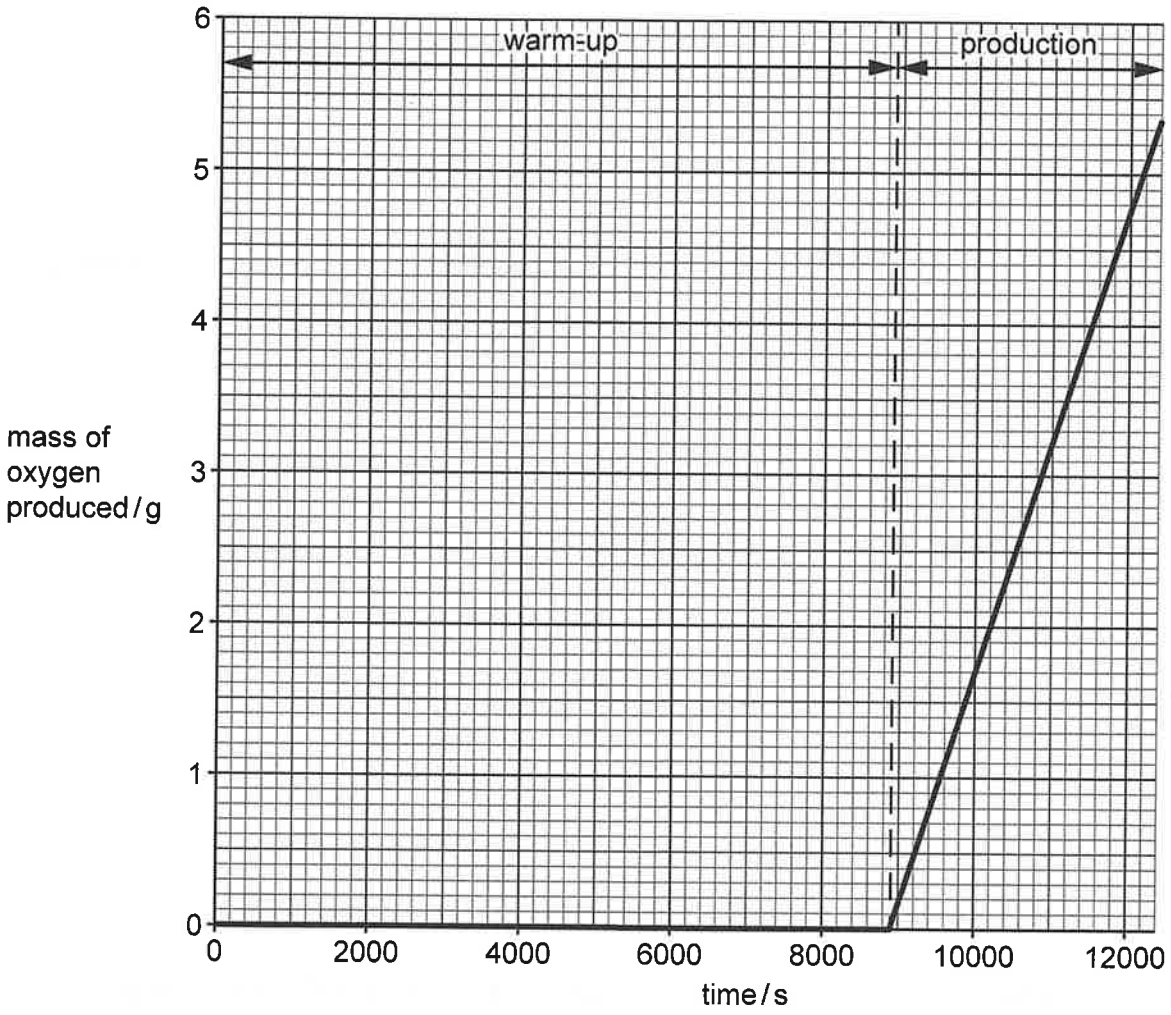

Fig. 8.2

(a) Explain why the half-life of plutonium-238 makes this isotope suitable for use in the RTG in Perseverance.

.....

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..... [1]

(b) Suggest why a radioisotope that emits α-particles is the most suitable type of emitter for an RTG.

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..... [1]

(c) Explain why it is important to prevent the plutonium in Perseverance from being absorbed by living organisms.

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..... [2]

(d) **(i)** The alpha decay of a plutonium-238 nucleus produces a nucleus of uranium (U).

Complete the equation for the decay of plutonium-238 ($^{238}_{94}$Pu).

$$^{238}_{94}\text{Pu} \rightarrow \text{.....}\ \text{U} + \text{.....}\ \alpha$$

[1]

(ii) Data for the decay in **(d)(i)** is shown in Table 8.2.

Table 8.2

nucleus	binding energy per nucleon /MeV
Pu	7.568
U	7.601
α	7.074

Determine the energy, in J, emitted when one nucleus of plutonium decays.

energy = ... J [2]

(iii) Determine the initial number of plutonium nuclei in the RTG in Perseverance.

number of nuclei = ... [1]

(iv) Determine the initial power output due to the decay of the plutonium in the RTG.

power = ... W [2]

(v) Determine the total number of alpha and the total number of beta decays that take place when one atom of the isotope of plutonium decays through the decay series into one atom of the stable isotope of lead.

number of alpha decays = ...

number of beta decays = ...

[2]

(e) **(i)** Explain what is meant by an exponential decrease.

.....

.....

..... [1]

(ii) Determine the electrical power output of the RTG at the end of the lifespan of Perseverance.

power = ... W [2]

(f) Determine the e.m.f. produced by a thermocouple in Perseverance.

e.m.f. = ... V [1]

(g) Calculate the gravitational field strength g_M on the surface of Mars. Show your working.

$$\frac{\text{radius of Earth}}{\text{radius of Mars}} = 1.88 \qquad \frac{\text{mass of Earth}}{\text{mass of Mars}} = 9.30$$

g_M = ... $N\,kg^{-1}$ [3]

(h) (i) Suggest how the power requirement for operating MOXIE can be provided by electrical energy from the RTG.

.....

..... [1]

(ii) Use Fig. 8.2 to determine the time, in hours, it took the RTG to generate enough energy for MOXIE to produce 5.37 g of oxygen the first time it was used.

Assume the oxygen was produced while the electrical power output from the RTG was still at its maximum value.

time = ... hours [2]

(iii) The oxygen gas produced by MOXIE the first time it was used was stored at a pressure of 610 Pa and a temperature of –60 °C.

Determine the volume of the stored oxygen.

Assume that oxygen is an ideal gas.

volume = ... m^3 [2]

[Total: 24]