M1.(a) $^{239}_{93}Np \rightarrow\ ^{239}_{94}Pu +\ ^{(0)}_{(-1)}\beta^- +\ ^{(0)}_{(0)}\bar{\nu}$ ✓✓

First mark for one anti-neutrino or one beta minus particle in any form e.g. e^-. If subscript and superscripts are given for these they must be correct but ignore the type of neutrino if indicated.
The second mark is for both particles and the rest of the equation.
Ignore the full sequence if it is shown but the Np to Pu must be given separately for the mark.

2

(b) (i) $T_{1/2}$ 2.0 → 2.1 × 10^5 s ✓
then substitute and calculate
$\lambda = \ln 2 / T_{1/2}$ ✓

$T_{1/2}$ may be determined from graph not starting at zero time.
Look for the correct power of 10 in the half-life – possible AE.

Or
(substitute two points from the graph into $A = A_o e^{-\lambda t}$)
e.g. $0.77 \times 10^{12} = 4.25 \times 10^{12} \exp(-\lambda \times 5 \times 10^5)$ ✓
then make λ the subject and calculate ✓
(the rearrangement looks like
$\lambda = [\ln (A_o / A)] / t$
or $\lambda = -[\ln (A / A_o)] / t$)

Allow the rare alternative of using the time constant of the decay
$A = A_o \exp(-t / t_{tc})$
from graph t_{tc} = 2.9→3.1 × 10^5 s ✓
$\lambda = 1 / t_{tc} = 3.4 \times 10^{-6}\ s^{-1}$ ✓
No CE is allowed within this question.

both alternatives give
λ = 3.3 → 3.5 × 10^{-6} s^{-1} ✓

For reference
$T_{1/2} = 2.0 \times 10^5$ s gives
$\lambda = 3.5 \times 10^{-6}\ s^{-1}$ and
$T_{1/2} = 2.1 \times 10^5$ s gives
$\lambda = 3.3 \times 10^{-6}\ s^{-1}$.

2

(ii) (using $A = N\lambda$
$N = 0.77 \times 10^{12} / 3.4 \times 10^{-6} = 2.2(6) \times 10^{17}$)

allow 2.2 → 2.4 × 10^{17} nuclei ✓

A possible route is find $N_o = A_o / \lambda$

then use $N = N_o e^{-\lambda t}$.

Condone lone answer.

1

(c) (i) uranium (– 235 captures) a neutron (and splits into 2 smaller nuclei / fission fragments) releasing more neutrons ✓

First mark for uranium + neutron gives more neutrons.

Ignore which isotope of uranium is used.

(at least one of) these neutrons go on to cause further / more splitting / fissioning (of uranium– 235) ✓

Second mark for released neutron causes more fission.
The word 'reaction□ may replace 'fission□ here provided 'fission / splitting of uranium□ is given somewhere in the answer.

2

(ii) **Escalate if clip shows critical mass in the question.**
the moderator slows down / reduces the kinetic energy of neutrons ✓
so neutrons are absorbed / react / fission (efficiently) by the uranium / fuel ✓

owtte
***Possible escalation**.*

2

(iii) neutrons are absorbed / collide with (by the nuclei in the shielding) ✓

Second mark is only given if neutrons appear somewhere in the answer.

converting the nuclei / atoms (of the shielding) into unstable isotopes (owtte)

No neutrons = no marks.

Making it neutron rich implies making them unstable.

2

[11]

M2.(a) ANY 2 from

- Slow moving neutrons or low (kinetic) energy neutrons

B1

- (They are in) thermal equilibrium with the moderator / Are in thermal equilibrium with other material (at a temperature of about 300 K)

B1

- Have energies of order of 0.025 eV
- Have (range of) KE similar to that of a gas at 300 K or room temperature

2

(b) (i) Use of $mgh = ½ mv^2$ by substitution or rearranges to make h the subject

PE for use of equation of motion (constant acceleration)

C1

0.086(1) (m) or 0.086(2) (m)

A1

2

(ii) Correct equation for conservation of momentum

$m_1u_1 \ (+ \ m_2u_2) = m_1v_1 + m_2v_2$

or states momentum before = momentum after **or** $p_{before} = p_{after}$

B1

(Correct clear Manipulation =) 0.065 (+ 0) = − 0.0325 + 0.0975

or −0.065 (+ 0) = 0.0325 − 0.0975 must see signs

Condone non−SI here:
65 (+0) = − 32.5 + 97.5

B1

States initial kinetic energy = final kinetic energy **or** **States** kinetic energy is conserved

Allow equivalent on RHS where masses are summed in one KE term

B1

(Correct clear Manipulation=) 0.04225 = 0.0105625 + 0.0316875

Or equivalent workings with numbers seen

and 0.04225 = 0.04225 / KE before = KE after

B1

4

(iii) (Percentage / fraction remaining after 1 collision =) ¼ = 25% **seen**

C1

OR
% remaining = 100 × ½ $m(1.3^2 − 0.65^2)$/ ½ $m1.3^2$
or hockey ball = 0.0317 **and** initial ke = 0.04225
or their KE_{hb} / 0.04225 or their KE_{hb} / their KE_T

75(%) range 75 to 76

A1

2

(iv) **Demonstrates:**
Slowing down / loss of KE of golf ball is like neutrons slowed down / Neutrons can lose KE by elastic collisions also

B1

Differs:
Collisions in a reactor are not always / rarely head-on
or
KE loss is variable
or
Collisions are not always elastic
or
Ratio of mass of neutron to mass of nucleus is usually much smaller in a reactor

B1

2

(v) Water

B1

1

[13]

M3.(a) the amount of energy required to separate a nucleus ✓
into its separate neutrons and protons / nucleons ✓

(or energy released on formation of a nucleus ✓
from its separate neutrons and protons / constituents ✓)

1st mark is for correct energy flow direction

2nd mark is for binding or separating nucleons (nucleus is in the question but a reference to an atom will lose the mark)

ignore discussion of SNF etc

both marks are independent

2

(b) (i) $2\,^{1}_{0}\text{n}$ or $^{1}_{0}\text{n} + ^{1}_{0}\text{n}$ ✓

must see subscript and superscripts

1

(ii) binding energy of U
= 235 × 7.59 ✓ (= 1784 (MeV))
binding energy of Tc and In
= 112 × 8.36 + 122 × 8.51 ✓
(= 1975 (MeV))
energy released (= 1975 – 1784) = 191 (MeV) ✓ (allow 190 MeV)

1st mark is for 235 × 7.59 seen anywhere
2nd mark for 112 × 8.36 + 122 × 8.51 or 1975 is only given if there are no other terms or conversions added to the equation (ignore which way round the subtraction is positioned)
correct final answer can score 3 marks

3

(iii) energy released
= 191 × 1.60 × 10^{-13} ✓
(= 3.06 × 10^{-11} J)
loss of mass (= E / c^2)
= 2.91 × 10^{-11} / (3.00 × $10^{8})^{2}$)
= 3.4 × 10^{-28} (kg) ✓
or
= 191 / 931.5 u ✓ (= 0.205 u)
= 0.205 × 1.66 × 10^{-27} (kg)
= 3.4 × 10^{-28} (kg) ✓

allow CE from (ii)
working must be shown for a CE otherwise full marks can be given for correct answer only

note for CE
answer = (ii) × 1.78 × 10^{-30}

(2.01 × 10^{-27} is a common answer)

2

(c) (i) line or band from origin, starting at 45° up to Z approximately = 20 reading $Z = 80$, $N = 110 \rightarrow 130$ ✓

initial gradient should be about 1 (ie Z = 20 ; N = 15 → 25) and overall must show some concave curvature. (Ignore slight waviness in the line)
if band is shown take middle as the line
if line stops at N > 70 extrapolate line to N = 80 for marking

1

(ii) fission fragments are (likely) to be above / to the left of the line of stability ✓

fission fragments are (likely) to have a larger N / Z ratio than stable nuclei
or
fission fragments are neutron rich owtte ✓
and become neutron or β^- emitters ✓

ignore any reference to α emission
a candidate must make a choice for the first two marks
stating that there are more neutrons than protons is not enough for a mark
1st mark reference to graph
2nd mark – high N / Z ratio or neutron rich
3rd mark beta <u>minus</u>
note not just beta

3

[12]

M4.(a) insert control rods (further) into the nuclear core / reactor ✓

a change must be implied for 2 marks
marks by use of (further) or (more)
allow answers that discuss shut down as well as power reduction

which will absorb (more) neutrons (reducing further fission reactions) ✓

If a statement is made that is wrong but not asked for limit the score to 1 mark (e.g. wrong reference to moderator)

2

(b) fission fragments / daughter products or <u>spent / used</u> fuel / uranium rods (allow) plutonium (produced from U-238) ✓

not uranium on its own

1

(c) (i) γ (electromagnetic radiation is emitted) ✓

A reference to α or β loses this first mark

as the energy gaps are large (in a nucleus) as the nucleus de-excites down discrete energy levels to allow the nucleus to get to the ground level / state ✓ mark for reason

2nd mark must imply energy levels or states

2

(ii) momentum / kinetic energy is transferred (to the moderator atoms)
or
a neutron slows down / loses kinetic energy (with each collision) ✓

(eventually) reaching speeds associated with thermal random motion or reaches speeds which can cause fission (owtte) ✓

2

[7]