Q1 FUSION REACTION (10 pts)

Part 1. Energy from fusion reaction (2.8 pts)

1.1 (a)	D-D: 3.270 MeV D-T: 17.59 MeV	0.1 pt 0.1 pt
1.1 (b)	$E_n = \left(\frac{m_x}{m_x + m_n}\right) Q$	0.6 pts
1.1 (c)	D-D: $E_n = 2.450$ MeV D-T: $E_n = 14.05$ MeV	0.1 pt 0.1 pt
1.2 (a)	D-D: 4.728×10^{-4} kg ($4.680 \times 10^{-4} - 4.775 \times 10^{-4}$ kg) D-T: 1.098×10^{-4} kg ($1.087 \times 10^{-4} - 1.108 \times 10^{-4}$ kg) P *Note: Answers within $\pm 1\%$ of these values are acceptable.*	0.25 pts 0.25 pts
1.2 (b)	5.285×10^{-4} kg ($5.232 \times 10^{-4} - 5.337 \times 10^{-4}$ kg) *Note: Answers within $\pm 1\%$ of this value are acceptable.*	0.25 pts
1.2 (c)	4.181×10^{2} kg	0.15 pt

1.2 (d)	3.808×10^6 $(3.769 \times 10^6 - 3.846 \times 10^6)$ *Note: Answers within $\pm 1\%$ of this value are acceptable.*	0.1 pt

Part 2. Tritium production (3.2 pts)

2.1	$2.468\ \text{MeV}$ $(2.443 - 2.493\ \text{MeV})$ *Note: Answers within $\pm 1\%$ of this value are acceptable.*	0.8 pts

2.2 (a)	$0.597\ \text{g}$ of ${}^3_1\text{H}$ $(0.590 - 0.603\ \text{g})$ *Note: Answers within $\pm 1\%$ of this value are acceptable.*	1.0 pt

2.2 (b)	$2.513 \times 10^5\ \text{kg}$ $(2.488 \times 10^5 - 2.538 \times 10^5\ \text{kg})$ *Note: Answers within $\pm 1\%$ of this value are acceptable.*	0.2 pts

Part 3. Overcoming the Coulomb barrier (4.0 pts)

3.1 (a)	$7.630 \times 10^{-14}\ \text{N} \cdot \text{m}$ $(7.553 \times 10^{-14} - 7.706 \times 10^{-14}\ \text{N} \cdot \text{m})$ *Note: Answers within $\pm 1\%$ of this value are acceptable. Alternate unit is joules or J.*	0.8 pts

3.1 (b)	$7.115 \times 10^{-14}\ \text{N} \cdot \text{m}$ $(7.044 \times 10^{-14} - 7.186 \times 10^{-14}\ \text{N} \cdot \text{m})$ *Note: Answers within $\pm 1\%$ of this value are acceptable. Alternate unit is joules or J.*	0.8 pts

3.2 (a)	D-D: 1.842×10^9 K $(1.824 \times 10^9 - 1.860 \times 10^9 \text{ K})$ D-T : 1.718×10^9 K $(1.701 \times 10^9 - 1.735 \times 10^9 \text{ K})$ *Note: Answers within ±1% of these values are acceptable.*	0.3 pts 0.3 pts

3.2 (b)	D-D: 121.5% (120.3 – 122.7%) D-T : 167.9% (166.2 – 169.6%) *Note: Answers within ±1% of these values are acceptable*	0.15 pts 0.15 pts

Part 4. Portable neutron generators (3.5 pts)

4.1	(a) D: $N_{s,D} = 7.566 \times 10^{21}\ \text{cm}^{-2}$ $(7.490 \times 10^{21} - 7.642 \times 10^{21}\ \text{cm}^{-2})$ (b) T: $N_{s,T} = 7.536 \times 10^{21}\ \text{cm}^{-2}$ $(7.461 \times 10^{21} - 7.612 \times 10^{21}\ \text{cm}^{-2})$ *Note: Answers within ±1% of these values are acceptable*	0.7 pts 0.7 pts

4.2	D-D: 2.005×10^{-5}A $(1.985 \times 10^{-5} - 2.025 \times 10^{-5}\text{ A})$ D-T : 6.869×10^{-8}A $(6.801 \times 10^{-8} - 6.938 \times 10^{-8}\text{ A})$ *Note: Answers within ±1% of these values are acceptable.*	0.7 pts 0.7 pts

4.3 (a)	$8.842 \times 10^4\ \text{n/cm}^2 \cdot \text{s}$ $(8.754 \times 10^4 - 8.930 \times 10^4\ \text{n/cm}^2 \cdot \text{s})$ *Note: Answer within ±1% of this value is acceptable.*	0.2 pts

4.3 (b)	$\phi_2 = \frac{{D_2}^2}{{D_1}^2}\phi_1 = \left(\frac{D_2}{D_1}\right)^2 \phi_1$	0.5 pts

Q2 STERILE INSECT TECHNIQUE FOR MOSQUITOES (10 pts)

Part 1. Absorbed Dose Measurement Using Fricke Dosimeter (4.5 points)

1.1 — 0.5 pt

$P\ (J\ h^{-1}) = 5.768 \times 10^{-4} AE$

$(\mathbf{5.710 \times 10^{-4}}$ **to** $\mathbf{5.826 \times 10^{-4} AE})$

Note: Answers within $\pm 1\%$ of this value are acceptable.

1.2 — 1.0 pt

$$P\ (J\ h^{-1} m^{-2}) = \frac{1.442 \times 10^{-4} AE}{\pi r^2} \quad or \quad \frac{4.590 \times 10^{-5} AE}{r^2}$$

$(\mathbf{1.428 \times 10^{-4}}$ **to** $\mathbf{1.456 \times 10^{-4}) AE/\pi r^2}$ (if with π)

$(\mathbf{4.544 \times 10^{-5}}$ **to** $\mathbf{4.636 \times 10^{-5}) AE/r^2}$ (if no π)

Note: Answers within $\pm 1\%$ of this value are acceptable.

1.3 — 1.5 pt

$\mathrm{DR} = 489.1\ Gy\ h^{-1}$ (1.0 pt);

$(\mathbf{484.2}$ **to** $\mathbf{494.0})\ \boldsymbol{Gy\ h^{-1}}$

$\mathrm{D} = 81.5\ Gy$ (0.5 pt);

$(\mathbf{80.70}$ **to** $\mathbf{82.33})\ \boldsymbol{Gy}$

Note: Answers within $\pm 1\%$ of this value are acceptable.

1.4 — 0.5 pt

$0.997\ \mu mol\ J^{-1}$

$(\mathbf{0.988}$ **to** $\mathbf{1.007})\ \boldsymbol{\mu mol\ J^{-1}}$

Note: Answers within $\pm 1\%$ of this value are acceptable.

1.5 — 1.0 pt (0.2 pt each)

Absorbed dose	No. of photon interactions
10	2.081×10^{11} $(\mathbf{2.060}$ **to** $\mathbf{2.101}) \times \mathbf{10^{11}}$
20	4.161×10^{11} $(\mathbf{4.119}$ **to** $\mathbf{4.203}) \times \mathbf{10^{11}}$
30	6.242×10^{11} $(\mathbf{6.179}$ **to** $\mathbf{6.304}) \times \mathbf{10^{11}}$

40	8.322 x 10^{11} $(8.239 \text{ to } 8.405) \times 10^{11}$
50	1.040 x 10^{12} $(1.030 \text{ to } 1.051) \times 10^{12}$

Note: Answers within $\pm 1\%$ of this value are acceptable.

Part 2. Egg Hatch and Dose in SIT (3.5 points)

2.1 11.60 Gy — 0.5 pt

$(11.48 \text{ to } 11.71)\ Gy$

Note: Answers within $\pm 1\%$ of this value are acceptable.

2.2 58.94 min or 58 min & 56 sec. — 1.0 pt

$(58.4 \text{ to } 59.5)\ min$

or $(58\ min\ 21\ sec \text{ to } 59\ min\ 32\ sec)$

Note: Answers within $\pm 1\%$ of this value are acceptable.

2.3 0.896 cm — 1.0 pt

$(0.887 \text{ to } 0.905)\ cm$

Note: Answers within $\pm 1\%$ of this value are acceptable.

2.4 (a) 0.05343 cm^2/g — 0.5 pt

$(0.0529 \text{ to } 0.0540)\ cm^2/g$

Note: Answers within $\pm 1\%$ of this value are acceptable.

2.4 (b) 14 sheets — 0.5 pt

Part 3. Competitiveness and Dose in SIT (2.0 points)

3.1	0.256 $(0.253 \quad \text{to} \quad 0.258)$ ***Note: Answers within $\pm 1\%$ of this value are acceptable.***	1.0 pt

3.2	20.21 Gy $(20.01 \quad \text{to} \quad 20.41)\ Gy$ ***Note: Answers within $\pm 1\%$ of this value are acceptable.***	1.0 pt

Q3 PARTICLES FOR DESTROYING CANCER (10 pts)

Part 1. Proton Stopping Power, Range, and Dose (5.0 pts)

1.1	Stopping power is defined as the rate of energy loss per unit path length by a particle traveling through a material.	0.2 pt
	LET is the average energy deposited/transferred to the material per unit path length.	0.2 pt

1.2	A: Electron	0.2 pt
	B: Photon	0.2 pt
	C: Proton	0.2 pt

1.3	$\frac{S}{\rho} = -\frac{dE}{\rho dx} = \frac{0.170}{\rho {\beta_v}^2}[F(\beta_v) - 4.31]$	0.5 pt
	Other acceptable answers: $\frac{S}{\rho} = -\frac{dE}{\rho dx} = \frac{0.17}{\rho {\beta_v}^2}[F(\beta_v) - 4.31]$; $\frac{S}{\rho} = -\frac{dE}{\rho dx} = \frac{0.17}{(\, g \cdot cm^{-3})\, {\beta_v}^2}[F(\beta_v) - 4.31]$	

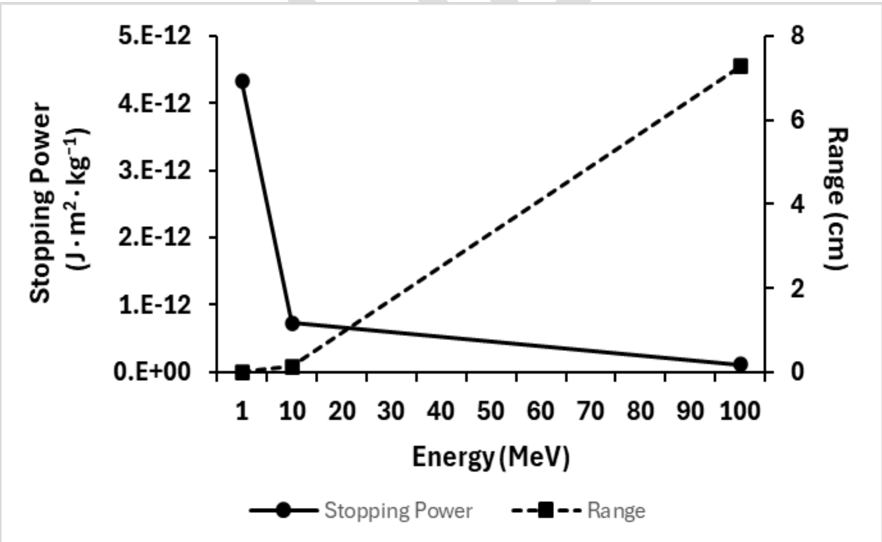
1.4 (a)	$1\ MeV: 0.046\ c = 1.38 \times 10^7\ m \cdot s^{-1}$	0.25 pt
	$10\ MeV: 0.145\ c = 4.34 \times 10^7\ m \cdot s^{-1}$	0.25 pt
	$100\ MeV: 0.428\ c = 1.28 \times 10^8\ m \cdot s^{-1}$	0.25 pt

1.4 (b)	$1\ MeV: \frac{S}{\rho} = -\frac{dE}{\rho dx} = 269\ MeV \cdot cm^2 \cdot g^{-1}$	0.25 pt
	$10\ MeV: \frac{S}{\rho} = -\frac{dE}{\rho dx} = 45.9\ MeV \cdot cm^2 \cdot g^{-1}$	0.25 pt

	$100\ MeV: \dfrac{S}{\rho} = -\dfrac{dE}{\rho dx} = 7.28\ MeV \cdot\ cm^2\ \cdot g^{-1}$ Other acceptable answers: $1\ MeV: 4.32 \times 10^{-12}\ J \cdot m^2 \cdot kg^{-1}$ $10\ MeV: 7.35 \times 10^{-13}\ J \cdot m^2 \cdot kg^{-1}$ $100\ MeV: 1.17 \times 10^{-13}\ J \cdot m^2 \cdot kg^{-1}$	0.25 pt

1.4 (c)	$1\ MeV: 0.00230\ or\ 2.30 \times 10^{-3}\ \ cm$ $10\ MeV: 0.129\ or\ or\ 1.29 \times 10^{-1}\ cm$ $100\ MeV: 7.27\ cm$ Other acceptable answers: $1\ MeV: R = 0.00230\ or\ 2.30 \times 10^{-3}\ g \cdot cm^{-2}$ $10\ MeV: R = 0.129\ or\ or\ 1.29 \times 10^{-1}\ g \cdot cm^{-2}$ $100\ MeV: R = 7.27\ g \cdot cm^{-2}$	0.25 pt 0.25 pt 0.25 pt

1.4 (d)



0.3 pt

Note: ACCEPT answer even if:
(1) Unit of Energy is in joules (J).
(2) Energy (1,10,100 MeV) is not graphed to the appropriate scale.
(3) Log_{10} of energy values is used in the graph.
(4) Obtained values (stopping power & range) are graphed with proton energy separately.

0.2 pt

The mass stopping power decreases, whereas the range of proton increases with increasing proton energy.

1.5 0.75 pt

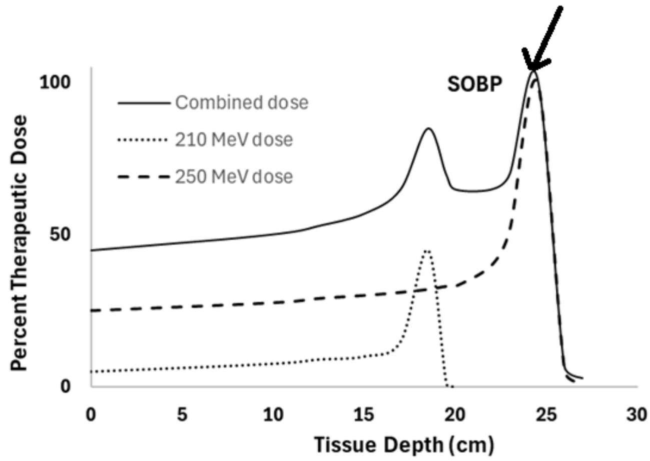
$$D = 1.46\ \frac{J}{kg}\ (or\ Gy)$$

Other acceptable answer:

$$D = 9.11\ \times 10^{9}\ \frac{MeV}{g}$$

Part 2. Proton Therapy (4.0 pts)

2.1 (a) 0.3 pt



2.1 (b) FALSE 0.3 pt

2.1 (c) TRUE 0.3 pt

2.1 (d)	D or D. 235 MeV	0.3 pt

2.2 1.0 pt

$$RBE = \frac{D_x}{D_p} = \frac{\sqrt{\left(\frac{\alpha}{\beta}\right)_x^2 + 4D_p\left(\frac{\alpha}{\beta}\right)_x RBE_{max} + 4D_p^2 RBE_{min}^2} - \left(\frac{\alpha}{\beta}\right)_x}{2D_p}$$

2.3 (a)

HaCat — 0.6 pt (0.2 pt each)

LET_d	RBE_{2Gy}
1.9	**1.06**
2.5	**1.08**
4.5	**1.12**

SKMel — 0.6 pt (0.2 pt each)

LET_d	RBE_{2Gy}
1.9	**1.16**
2.5	**1.19**
4.5	**1.29**

2.3 (b)

RBE increases with increasing LET_d. — 0.2 pt

Higher (or lower) RBE values can be expected for tissues with low (or high) $(\alpha/\beta)_x$ given similar LET_d values. — 0.2 pt

Note: Exact word usage not required. Accept answers with similar interpretation.

2.3 (c) **HaCat** — 0.6 pt (0.2 pt each)

LET_d	$D_x(Gy)$
1.9	**2.13**
2.5	**2.15**
4.5	**2.24**

SKMel — 0.6 pt (0.2 pt each)

LET_d	$D_x(Gy)$
1.9	**2.32**
2.5	**2.38**
4.5	**2.57**

Q4 MASS AND ABUNDANCE OF ISOTOPES (10 pts)

Part 1. Basic operation of a Mass Spectrograph (2.1 pts)

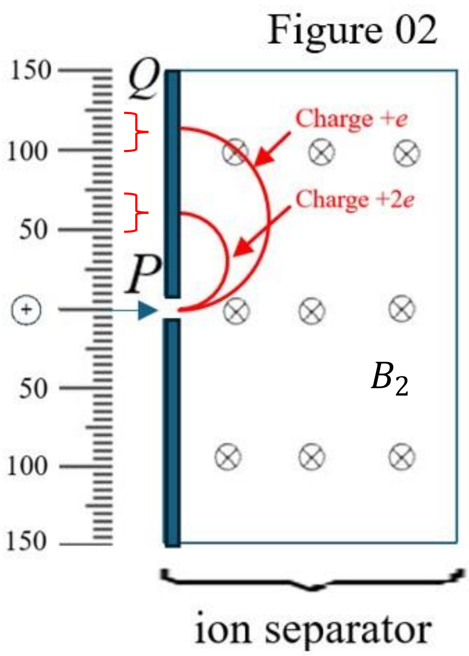
1.1	1.923×10^{-16} J Accept 1.91 – 1.93	0.3 pt
1.2	1.40×10^{5} m/s Accept 1.3 – 1.5	0.4 pt
1.3. (a)	oz direction	0.3 pt
1.3 (b)	0.14 T Accept 0.13 – 0.15	0.7 pt
1.3 (c)	140.00 km/s	0.4 pt

Part 2. Motion of ions inside the ion separator (3.2 pts)

2.1	116 cm	0.7 pt

2.2	0.01 u	1.0 pt

2.2



For correct direction for both ions		0.6 pt
For correct dimensions for both ions		0.6 pt

Part 3: Mass spectrometers (1.6 pts)

3.1	$m_{min} = 5.51$ u Accept 5.50-5.52 $m_{max} = 88.2$ u Accept 88.1 – 88.2	0.5 pt 0.5 pt

3.2	89.2 Accept 89.1 – 89.3	0.6 pt

Part 4: Determining the age of rock samples (3.4 pts)

4.1 (a)	$N_P(t_1) + N_D(t_1) = N_P(t_0) + N_D(t_0)$	0.4 pt

4.1 (b)	$G = \left[e^{\lambda(t_1 - t_0)} - 1\right]$	0.7 pt

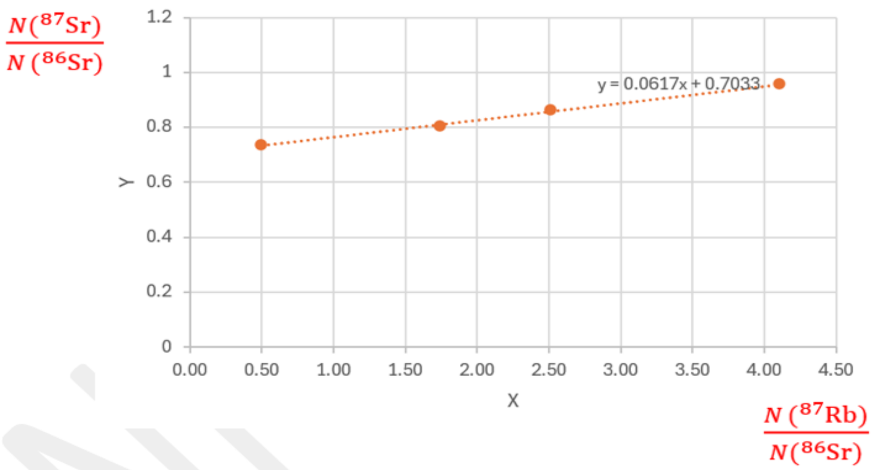
4.2 (a)

0.8 pt *(0.1 pt for each entry)*

Table 1. Nuclide ratios for the rock samples

Rock Sample	$\frac{N(^{87}\mathrm{Rb})}{N(^{86}\mathrm{Sr})}$	$\frac{N(^{87}\mathrm{Sr})}{N(^{86}\mathrm{Sr})}$
1	2.51	0.864
2	0.50	0.736
3	1.74	0.804
4	4.11	0.956

4.2 (b)



For the selection of the correct axes	0.2 pts
For the correct marking of the points (0.1/each)	0.4 pts

4.2 (c)

Gradient = 0.0617
Accept 0.061 – 0.063

0.3 pt

4.2 (d)

$4.15 \times 10^9\ years \sim 4.2\ billion\ years$

0.6 pt

Q5 ADVANTAGES OF USING LOW ENRICHED URANIUM IN NUCLEAR REACTORS (10 pts)

For the boxed results containing numeric answers, three values are given: low value, exact value, high value. Exact value is the result obtained when computations are performed starting from the problem given without rounding-off until final answer. The low and high value corresponds to ±5% of the exact value. **Numerical results ranging from the low value up to the high value are considered correct regardless of how many significant figures are presented.** This was done to accommodate examinee solutions implementing the correct process but failed to follow the instruction not to truncate in intermediate calculations.

Part 1. Uranium Enrichment (3.5 pts)

1.1 (a)

(i) — 0.05 pt

$$M_F = M_P + M_T$$

(ii) — 0.05 pt

$$x_F M_F = x_P M_P + x_T M_T$$

1.1 (b) — 0.3 pt

$$M_F = \frac{x_T - x_P}{x_T - x_F} M_P$$

$$M_F = \frac{x_P - x_T}{x_F - x_T} M_P$$

$$M_P = \frac{x_T - x_F}{x_T - x_P} M_F$$

$$M_P = \frac{x_F - x_T}{x_P - x_T} M_F$$

Any of the 4 possible answers will merit full credit (0.3 pt)

1.2 (a) — 0.5 pt

Low Value	Exact Value	High Value
170.5 M_{235}	179.5 M_{235}	188.5 M_{235}

Or

Low Value	Exact Value	High Value
170.5	179.5	188.5

1.2 (b)

0.5 pt

Low Value	Exact Value	High Value
$180.8\ M_{235}$	$190.4\ M_{235}$	$199.9\ M_{235}$

Or

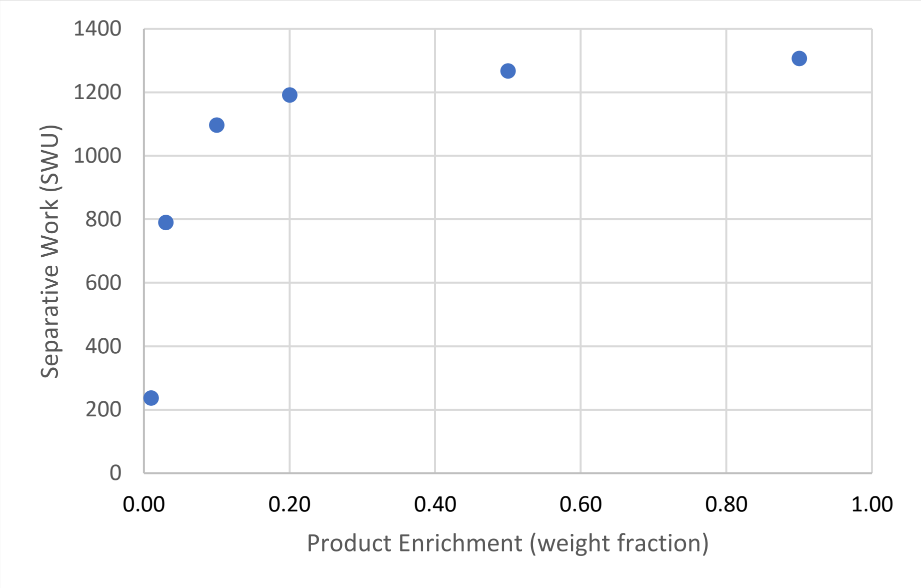
Low Value	Exact Value	High Value
180.8	190.4	199.9

1.3 (a)

1.2 pt

0.2 pt per answer for a given x_P

x_P	SWU		
	Low Value	Exact Value	High Value
1.0%	225.4	237.3	249.2
3.0%	750.4	789.9	829.4
10.0%	1042	1097	1152
20.0%	1132	1192	1251
50.0%	1204	1268	1331
90.0%	1241	1307	1372

1.3 (b)	 Grading Rubric: Case for 0.6 pt: • All answers to problem 1.3a are correct and data points placed appropriately. Case for 0.4 pt: • Correct trend of steep climb from 0 to 0.2 weight fraction then gradual increase thereafter. Acceptable even without dots/markers. Acceptable even if the y-axis range is missing or incorrect. Case for 0.2 pt: • Examinee wrote values in y-axis regardless of the range	0.6 pt

1.3 (c)	Difficult for enrichment plants to achieve enrichment from a lower percentage up to the 20% mark. After the 20% mark, we can see that a lesser amount of work is needed to get to the higher enrichment values. Or More work to enrich from low percentage up to 20% than increasing beyond 20% to higher enrichment level.	0.3 pt

Grading Rubric:

Full credit is given when any of the following thoughts are expressed:

- More effort required to enrich from low value up to 0.2 weight fraction (20% enrichment)
- Less effort required to enrich above 0.2 weight fraction (20% enrichment)

Part 2. Energy from ^{235}U and ^{238}U (4.0 pts)

2.1 0.6 pt

Low Value	Exact Value	High Value
3864 kg	4068 kg	4271 kg

2.2a 0.6 pt

Low Value	Exact Value	High Value
4384 kg	4615 kg	4846 kg

2.2b 0.6 pt

Low Value	Exact Value	High Value
5127 kg	5396 kg	5666 kg

2.2c 0.8 pt

Low Value	Exact Value	High Value

9.295×10^5 kg	9.785×10^5 kg	1.027×10^6 kg

Or

Low Value	Exact Value	High Value
929,500 kg	978,500 kg	1,027,000 kg

2.2d 0.2 pt

Low Value	Exact Value	High Value
6.199×10^5 kg	6.525×10^5 kg	6.852×10^5 kg

Or

Low Value	Exact Value	High Value
619,900 kg	652,500 kg	685,200 kg

2.3 0.4 pt 0.8 pt

^{236}U

Low Value	Exact Value	High Value
742.3 kg	781.4 kg	820.5 kg

Or

Low Value	Exact Value	High Value
745.7 kg	784.9 kg	824.2 kg

^{240}Pu

Low Value	Exact Value	High Value
941.6 kg	991.2 kg	1040.8 kg

Or

Low Value	Exact Value	High Value
945.6 kg	995.3 kg	1045.1 kg

Part 3. Criticality Accident (2.5 pts)

3.1 0.5 pt

Low Value	Exact Value	High Value
0.4365 kg TNT	0.4595 kg TNT	0.4825 kg TNT

3.2 1.0 pt

Low Value	Exact Value	High Value
5.279 Sv	5.557 Sv	5.835 Sv

3.3

$E_{neutrons}$

0.6 pt
0.3 pt
0.1 pt

Low Value	Exact Value	High Value
178.9 Sv	188.3 Sv	197.7 Sv

E_{total}

Low Value	Exact Value	High Value
184.1 Sv	193.8 Sv	203.5 Sv

Which type of ionizing Radiation:

Neutron or Neutrons