Montogue

PE Nuclear Engineering

◆40 Practice Questions

Lucas Monteiro Nogueira

Here's a set of 40 fully solved problems for applicants to the PE Nuclear exam. The problems were taken from a carefully researched assortment of textbooks. All problems are solved step by step. Enjoy! ■

PROBLEMS

Problem 1. The activity of a radioisotope is found to decrease by 14% within one week. The half-life (days) of this isotope is most nearly:

(A) 27
(B) 32
(C) 37
(D) 42

Problem 2. A sample initially contains 2.0 GBq of ^{90}Sr (half-life 29.1 years) and 0.6 GBq of its daughter nuclide ^{90}Y (half-life 64.0 hours). The activity (GBq) of the yttrium-90 after 8 days will be, most nearly:

(A) 0.6
(B) 0.69
(C) 1.38
(D) 1.82

Problem 3. The dose rate at a point *P* close to a source of cobalt-60 is 320 μSv/h. The half-value layer of lead for gamma radiation from Co-60 decay has been estimated at 12.5 mm. Accordingly, in order to reduce the dose rate at *P* to 20 μSv/h, the minimum lead thickness (mm) separating the point in question from the cobalt source is most nearly:

(A) 25
(B) 40
(C) 50
(D) 60

Problem 4. Metallic cesium-137 has photoelectric work function equal to 1.8 eV. Which of the following alternatives best approximates the maximum kinetic energy (eV) of electrons extracted from a ^{137}Cs sample upon irradiation with light of wavelength equal to 300 nm?

(A) 1.8
(B) 2.3
(C) 2.8
(D) 4.1

Problem 5. The energy loss in Compton scattering is greatest for a scattering angle θ equal to:
(A) 45°
(B) 90°
(C) 120°
(D) 180°

Problem 6. How many elastic scatters, on the average, are required to slow a 2-MeV neutron to below 1 eV in oxygen-16 (^{16}O)?
(A) 121
(B) 180
(C) 243
(D) 405

Problem 7. A neutron initially has an energy of 3 MeV, which is reduced to 1.2 MeV upon slowing down in a medium. The neutron then undergoes a second scattering collision, further reducing its energy to 0.8 MeV. The change in lethargy of the neutron in the second collision is most nearly:
(A) 0.40
(B) 0.46
(C) 0.70
(D) 0.92

Problems 8 and 9

8. A ^{137}Cs point source in air has an activity of 1100 μCi. Gamma photons from ^{137m}Ba with energy 0.6 MeV are emitted with a frequency of 0.845 per decay of ^{137}Cs. The linear attenuation coefficient for 0.6-MeV particles travelling in air is 0.036 cm^{-1}. At a distance of 30 centimeters from the source, the uncollided flux density ($cm^{-2} \cdot s^{-1}$) is most nearly:
(A) 515
(B) 1030
(C) 1545
(D) 2060

9. Which of the following alternatives best approximates the dose equivalent rate (μSv/hr) in tissue at a distance of 30 cm from the point source described in the previous problem? Assume charged particle equilibrium and use a quality factor of 1. Take (μ/ρ) = 0.0296 cm^2/g as the attenuation coefficient of water for 0.6-MeV photons.
(A) 8
(B) 12
(C) 18
(D) 23

Problems 10 and 11

The following table lists radiation weighting factors (w_R) listed in NCRP Report No. 116.

Radiation	w_R
X and γ-rays, electrons, positrons, and muons	1
Neutrons, energy 10 keV to 100 keV	10
Neutrons, energy >100 keV to 2 MeV	20
Neutrons, energy >2 MeV to 20 MeV	10
Alpha particles, fission fragments, and nonrelativistic heavy nuclei	20

The following table lists tissue weighting factors (w_T) for several tissues/organs.

Tissue/organ	w_T
Whole body	1.00
Gonads	0.20
Bone marrow (red)	0.12
Stomach	0.12
Liver	0.05
Thyroid	0.05

10. During the year, a worker receives 15 mGy externally from uniform, whole-body gamma radiation. In addition, the worker withstands annual doses of 2 mGy from internally deposited alpha particles in the gonads and 4 mGy from 30-keV neutrons in the thyroid. The annual effective dose for this worker is most nearly:
(A) 15 mSv
(B) 20 mSv
(C) 25 mSv
(D) 30 mSv

11. Reconsider the worker described in the previous problem. In addition to the effective dose calculated in the previous problem, how much additional 30-keV neutron dose to the thyroid can the worker withstand before the effective annual limit of 50 mSv is achieved?
(A) 20 mGy
(B) 30 mGy
(C) 40 mGy
(D) 50 mGy

Problem 12. In which of the following phases of the cell cycle is a cell most sensitive to ionizing radiation?
(A) G1
(B) G2
(C) S
(D) M

Problem 13. The initial concentration of boron in a 10,000-ft^3 reactor coolant system is 1500 ppm. Approximately what volume (ft^3) of solution of concentration 8000 ppm should be added to achieve a value of 1600 ppm in the coolant system?
(A) 156
(B) 181
(C) 204
(D) 232

Problems 14 and 15
14. The neutron flux in a bare spherical reactor of radius 50 cm is given by

$$\phi = 5\times10^{13}\frac{\sin(0.0628r)}{r}\ \text{neutrons/cm}^2\text{-sec}$$

where r is measured from the center of the reactor. The diffusion coefficient for the system is 0.80 cm. The maximum value of the flux ($n\cdot cm^{-2}\cdot s^{-1}$) in the reactor is most nearly:
(A) 3×10^{11}
(B) 3×10^{12}
(C) 7×10^{12}
(D) 9×10^{13}

15. What is, most nearly, the neutron current density ($n\cdot cm^{-2}\cdot s^{-1}$, absolute value) at a distance of 20 cm from the center of the spherical reactor?
(A) 5.6×10^{9}
(B) 2.8×10^{10}
(C) 5.6×10^{10}
(D) 3.8×10^{11}

Problem 16. What is, most nearly, the burnup rate (grams/day) of a 600 MWe, U-235 fueled reactor if the recoverable energy per fission is 200 MeV and the plant efficiency is 30%?
(A) 490
(B) 630
(C) 1600
(D) 2110

Problem 17. A radioactive waste sample contains appreciable amounts of plutonium-241 (^{241}Pu) and krypton-85 (^{85}Kr). As the waste ages, which of the following isotopes is likely to be building up in the waste?
(A) $^{235}_{92}\mathrm{U}$
(B) $^{236}_{92}\mathrm{U}$
(C) $^{242}_{95}\mathrm{Am}$
(D) $^{85}_{37}\mathrm{Rb}$

Problem 18. For a spherical, thermal, homogeneous, water-moderated reactor with radius equal to 80 cm, what is, most nearly, the infinite multiplication factor required for the reactor to be critical? Take 8.1 cm^2 and 27 cm^2 as the thermal diffusion area and neutron age of water, respectively.
(A) 1.025
(B) 1.054
(C) 1.066
(D) 1.081

Problem 19. Estimate the resonance escape probability p for a homogeneous uranium-graphite mixture in which the ratio of moderator-to-fuel atoms is 450. The resonance integral of the uranium is 277 b, the epithermal scattering cross-section of carbon is 4.66 b, and the average logarithmic energy decrement for carbon may be taken as 0.16.
(A) $p \approx 0.215$
(B) $p \approx 0.433$
(C) $p \approx 0.611$
(D) $p \approx 0.637$

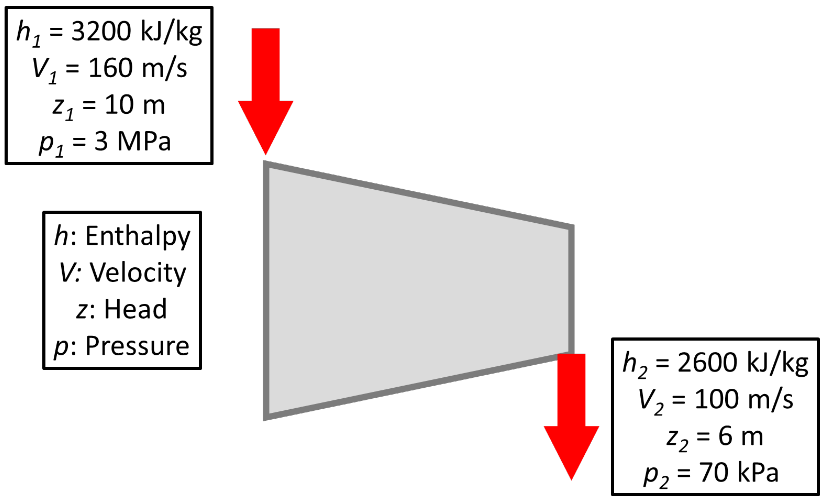
Problem 20. If the power density of a UO_2 cylindrical fuel pin of radius 0.6 cm is 500 W/cm^3, what is the heat flux q across the fuel rod surface? If the temperatures of rod surface and coolant are 300°C and 250°C, respectively, what must the heat transfer coefficient h be?
(A) q = 150 W/cm^2 h = 2.0 W/cm^2·°C
(B) q = 150 W/cm^2 h = 3.0 W/cm^2·°C
(C) q = 300 W/cm^2; h = 2.0 W/cm^2·°C
(D) q = 300 W/cm^2; h = 3.0 W/cm^2·°C

Problem 21. A monoatomic ideal gas (γ = 1.67, molar mass = 50) at 300 K is compressed adiabatically from 0.2 MPa to 0.4 MPa. The universal gas constant may be taken as 8314 J/kmol·K. The work (kJ/kg) involved in the compression of the gas is most nearly:
(A) 16
(B) 24
(C) 32
(D) 40

Problem 22. A Carnot engine operates between 327°C and 27°C. If the engine produces 180 kJ of work, what is the entropy change (kJ/K) during heat addition?
(A) 0.3
(B) 0.6
(C) 1.2
(D) 1.5

Problems 23 and 24

The inlet and the outlet conditions of flow for an adiabatic steam turbine are as indicated in the following illustration.



23. If the mass flow rate of steam through the turbine is 20 kg/s, the power output (MW) of the turbine is, most nearly:

(A) 12.157
(B) 12.941
(C) 168.001
(D) 168.785

24. Assume the above turbine to be part of a simple Rankine cycle. The density of water at the inlet to the pump is 1000 kg/m^3. Ignoring kinetic and potential energy effects, the specific work (kJ/kg) supplied to the pump is, most nearly:

(A) 0.293
(B) 0.351
(C) 2.930
(D) 3.510

Problems 25 and 26

A PWR is to be reloaded with a batch of fuel described by the following data.

Batch size	24,600 kilograms of U-235
Enrichment	3.2 w/o U-235
Tails	0.4 w/o U-235

Costs and financial data that may apply to this reload are listed below.

Enrichment cost	\$98 per separative work unit
U_3O_8 cost	\$23.20 per kg of U_3O_8
Chemical conversion cost	\$5.40 per kg of uranium in UF_6
Fabrication cost	\$220 per kg of uranium

Though losses do occur in conversion and in fabrication, neglect them in any calculations for problems 25 and 26.

25. Ignoring conversion, the cost (dollars) of 1 kg of U in natural feed material is, most nearly:

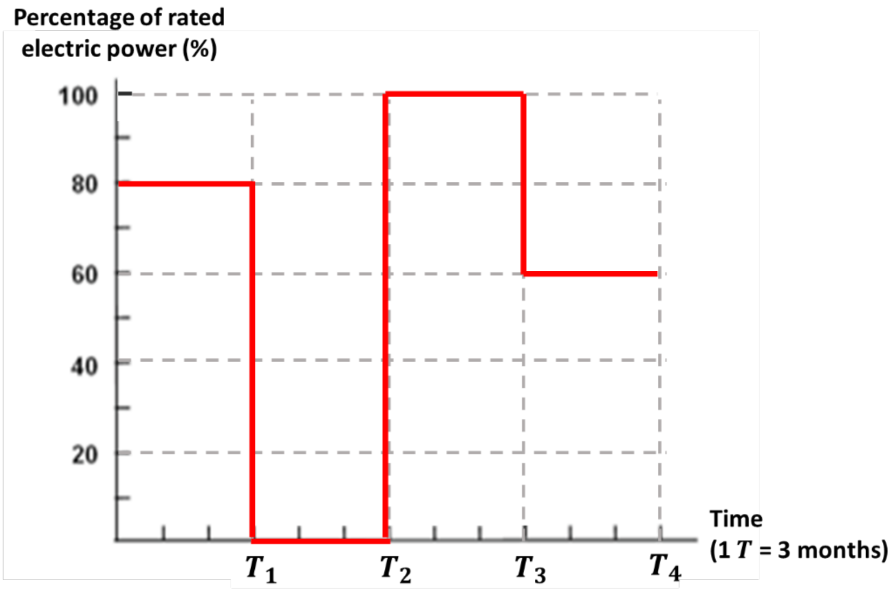
(A) 26.1
(B) 27.4
(C) 28.3
(D) 31

26. Starting with natural uranium feed, the total cost (in millions of dollars) of a batch reload is most nearly:

(A) 16
(B) 18.2
(C) 20.3
(D) 24

Problems 27 and 28

A 800 MW_e plant operates with the following power history for a period of one year. As shown, in the trimester spanning T_1 to T_2 the plant was shut down for scheduled maintenance and upgrades.



27. What is the availability factor?
(A) 0.2
(B) 0.5
(C) 0.75
(D) 0.9

28. What is the capacity factor?
(A) 0.55
(B) 0.6
(C) 0.65
(D) 0.7

Problem 29. The reactivity in a reactor fueled with U-235 changes by 0.3% due to an outward rod shim. What is, most nearly, the reactivity change in cents?
(A) 46
(B) 54
(C) 62
(D) 70

Problem 30. A 100-cm-long control rod has an integral worth of 50 cents when totally inserted in a reactor core. Approximately how much reactivity (cents) is introduced into the reactor when the rod is pulled one-quarter of the way out?
(A) 33
(B) 35
(C) 39
(D) 46

Problems 31 and 32

31. A ^{235}U-fueled reactor originally operating at a constant power of 1 milliwatt is placed on a positive 10-minute period. At approximately what time (min) will the reactor power level reach 1 megawatt?
(A) 90
(B) 150
(C) 210
(D) 270

32. The reactor in the previous problem is scrammed by the instantaneous insertion of 5 dollars of negative reactivity after having reached a constant power level of 1 megawatt. Approximately how long (min) does it take for the power level to drop to 1 milliwatt?
(A) 25
(B) 40
(C) 105
(D) 250

Problem 33. Match the detector types with the type of radiation they most commonly measure.

Detector type	Radiation type
P. Surface barrier	**I.** Alpha
Q. Bismuth germanate	**II.** Beta
R. Proton recoil	**III.** Gamma
S. Plastic scintillator	**IV.** Neutron

(A) P.II; Q.III; R.IV; S.I;
(B) P.I; Q.III; R.IV; S.II;
(C) P.I; Q.IV; Q.III; S.II;
(D) P.II; Q.I; R.III; S.IV;

Problem 34. A flow counter exhibits an average background rate of 1.21 counts per minute. Assuming that Poisson statistics are valid for this device, the probability that a 2-minute count measurement will register at least one count is, most nearly:
(A) 0.81
(B) 0.86
(C) 0.91
(D) 0.96

Problem 35. Anthracene emits scintillation photons of wavelength 447 nm in response to incident radiation. If 1 MeV of energy is deposited in an anthracene crystal and 32,000 scintillation photons are produced, the scintillation efficiency is most nearly:
(A) 5%
(B) 9%
(C) 13%
(D) 17%

Problem 36. The entrance port of a free-air ionization chamber has a diameter of 0.4 cm, and the length of the collecting plates is 5 cm. Exposure to an X-ray beam produces a steady current of 0.3 nA for 80 seconds. The temperature is 25°C and the pressure is 780 torr. The total exposure (R) registered by the ionization chamber in this event is, most nearly:
(A) 30
(B) 60
(C) 90
(D) 120

Problem 37. The following radiation counter data were obtained from sources A and B of the same isotope. The ratio of the activity of source B to the activity of source A is most nearly:

	Counts registered	Timing period
Source A + background	251 counts	5 min
Source B + background	717 counts	2 min
Background	51 counts	10 min

(A) 6.74
(B) 7.14
(C) 7.84
(D) 8.54

Problem 38. Counters A and B are nonparalyzable with dead time of 30 and 100 μs, respectively. At approximately what true event rate (sec^{-1}) will dead time losses in counter B be twice as great as those for counter A?
(A) 10,100
(B) 11,800
(C) 13,300
(D) 14,600

Problem 39. During the 10-day period encompassed by the accident at Three Mile Island, local residents were most prominently exposed to emissions of two radioactive nuclides, namely:
(A) Krypton-85 and cesium-137.
(B) Xenon-133 and cobalt-60.
(C) Krypton-85 and iodine-131.
(D) Xenon-133 and krypton-85.

Problem 40. Regarding the 2011 Fukushima nuclear disaster, which of the following statements is **false**?
(A) All units at Fukushima Daiichi plant consisted of boiling water reactors (BWRs).
(B) The Tohoku earthquake and tsunami damaged both the Fukushima Daiichi ('number one') and Daini ('number two') plants. Hydrogen explosions ensuing from oxidation of zirconium cladding contributed to damage at Fukushima Daiichi plant, but no such explosions were observed in any of the units at Fukushima Daini.
(C) Japan's Nuclear and Industrial Safety Agency initially placed the severity of the disaster at level 5 in the International Nuclear Events Scale, but soon downgraded it as the emissions of iodine-131 in the affected region were re-evaluated to be much milder than initially estimated.
(D) Tokyo Electric Power Company reported that, over the course of the disaster and the ensuing response operations, workers in the Fukushima site were exposed to high radiation levels. However, no casualties resulting from acute radiation syndrome were attributed to the disaster.

ANSWER KEY

Problem	Answer	Problem	Answer
1	B	21	B
2	D	22	B
3	C	23	A
4	B	24	C
5	D	25	B
6	A	26	C
7	B	27	C
8	B	28	A
9	C	29	A
10	C	30	D
11	D	31	C
12	D	32	A
13	A	33	B
14	B	34	C
15	C	35	B
16	D	36	D
17	D	37	C
18	B	38	C
19	B	39	D
20	B	40	C

SOLUTIONS

1 ➡ B

Solving the radioactive decay law $A(t)/A(0) = exp(-\lambda t)$ for time, we have

$$t = -\frac{1}{\lambda}\ln\left[\frac{A(t)}{A(0)}\right]$$

We are given that $A(t = 7\text{ d})/A(0) = 0.86$, so that

$$7.0 = -\frac{1}{\lambda}\ln(0.86)$$

$$\therefore \lambda = -\frac{\ln(0.86)}{7.0} = 0.0215\text{ d}^{-1}$$

The half-life of the isotope in question follows as

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{0.0215} = \boxed{32.2\text{ days}}$$

2 ➡ D

The activity of strontium-90 decays exponentially following the usual exponential law $A_1(t) = A_1(0)e^{-\lambda_1 t}$, while that of yttrium-90 evolves according to

$$A_2(t) = A_2(0)e^{-\lambda_2 t} + \frac{\lambda_2 A_1(0)}{\lambda_2 - \lambda_1}\left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right)\ \text{(I)}$$

The decay constants are

$$\lambda_1 = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{29.1\times 365} = 6.53\times 10^{-5}\ \text{d}^{-1}$$

and

$$\lambda_2 = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{(64.0/24)} = 0.260\text{ d}^{-1}$$

Substituting in (I),

$$A_2(12) = 0.6\times e^{-0.260\times 8} + \frac{0.260\times 2.0}{0.260-(6.53\times 10^{-5})}\times\left(e^{-(6.53\times 10^{-5})\times 8} - e^{-0.260\times 8}\right)$$

$$\therefore \boxed{A_2(12) = 1.82\text{ GBq}}$$

3 ➡ C

We want to decrease the dose rate from 320 μSv/h to 20 μSv, which implies a 16-fold decrease. To achieve this level of protection, we require four half-value layers (2 × 2 × 2 × 2 = 16), hence the required thickness will be 4 × 12.5 = 50 mm.

4 ➡ B

The maximum kinetic energy is given by

$$KE_{\max} = \frac{hc}{\lambda} - W = \frac{(4.14\times 10^{-15})\times(3.0\times 10^{8})}{300\times 10^{-9}} - 1.8 = \boxed{2.34\text{ eV}}$$

5 ➡ D

The maximum energy loss in Compton scattering occurs for a scattering angle θ = 180°.

6 ➡ A

The first step is to compute the logarithmic energy loss ξ per elastic scatter,

$$\xi = 1 + \frac{\alpha}{1-\alpha}\ln\alpha$$

where

$$\alpha = \left(\frac{A-1}{A+1}\right)^2 = \left(\frac{16-1}{16+1}\right)^2 = 0.7785$$

so that

$$\xi = 1 + \frac{0.7785}{1-0.7785} \times \ln(0.7785) = 0.120$$

The average number *n* of scatters required to decrease a neutron's kinetic energy from $E_1 = 2\times10^6$ eV to $E_2 = 1$ eV follows as

$$n = \frac{1}{\xi}\ln\left(\frac{E_1}{E_2}\right) = \frac{1}{0.120} \times \ln\left(\frac{2\times10^6}{1}\right) = \boxed{121}$$

7 ➡ B

The initial lethargy is

$$u_{\text{initial}} = \frac{\ln(E_{\text{source}})}{E_{\text{initial}}} = \frac{\ln(3.0)}{1.2} = 0.916$$

whereas the final lethargy is

$$u_{\text{final}} = \frac{\ln(E_{\text{source}})}{E_{\text{final}}} = \frac{\ln(3.0)}{0.8} = 1.373$$

so that

$$\Delta u = u_{\text{final}} - u_{\text{initial}} = 1.373 - 0.916 = \boxed{0.457}$$

8 ➡ B

This is a straightforward application of the uncollided flux density formula

$$\phi^o = \frac{S_p}{4\pi r^2}\exp(-\mu r)$$

$$\therefore \phi^{\text{o}} = \frac{(1100\times10^{-6}\ \text{Ci})\times(3.7\times10^{10}\ \text{decays/Ci})\times(0.845\ \text{photons/decay})}{4\pi\times(30\ \text{cm})^2}\times e^{-0.036\times30}$$

$$\therefore \boxed{\phi^o = 1030\ \text{cm}^{-2}\cdot\text{s}^{-1}}$$

9 ➡ C

Assuming charged particle equilibrium, the absorbed dose rate equals the kerma rate. In turn, the kerma rate can be approximated as

$$\dot{K} = 1.602\times10^{-10} E\left(\frac{\mu_{\text{tr}}(E)}{\rho}\right)\phi^o$$

with the kerma in units of Gy/s, *E* in MeV, (μ_{tr}/ρ) in cm^2/g, and ϕ^o in cm^{-2}s^{-1}. Approximating tissue as water, we may write, noting that dose equivalent $\dot{H}$ equals the quality factor for photons (*QF* = 1) times the absorbed dose $\dot{D}$:

$$\dot{H} = QF\times\dot{D} = 1.0\times1.602\times10^{-10} E\left(\frac{\mu(E)}{\rho}\right)\phi^{\text{o}}$$

$$\therefore \dot{H} = 1.0\times(1.602\times10^{-10})\times0.0296\times1030 = 4.88\times10^{-9}\ \mu\text{Gy/s}$$

$$\therefore \boxed{\dot{H} = 17.6\ \mu\text{Sv/h}}$$

10 ➡ C

Using the appropriate radiation weighting factors, we have the dose contributions

$$H_{\text{Whole-body}} = 15\times1.0 = 15\ \text{mSv}$$
$$H_{\text{Gonads}} = 2\times20 = 40\ \text{mSv}$$
$$H_{\text{Thyroid}} = 4\times10 = 40\ \text{mSv}$$

Then, using the appropriate tissue weighting factors, we compute the effective dose

$$E = 15\times1.0 + 40\times0.20 + 40\times0.05 = \boxed{25\ \text{mSv}}$$

11 ➡ D

The dose calculated in the previous problem was 25 mSv, hence the worker can receive an additional 25 mSv before the 50 mSv threshold is reached. We first compute the equivalent dose to the thyroid from the effective dose,

$$H_{\text{Thyroid}} \times 0.05 = 25$$

$$\therefore H_{\text{Thyroid}} = 500 \text{ mSv}$$

Then, noting that w_R = 10 for 50-keV neutrons,

$$500 = 10 \times D_{\text{Thyroid}}$$

$$\therefore D_{\text{Thyroid}} = \frac{500}{10} = \boxed{50 \text{ mGy}}$$

12 ➡ D

Cells are particularly vulnerable to ionizing radiation in late G2 and during M (mitosis), presumably because in these parts of the cell cycle there is no time for adequate repair before chromosome segregation takes place.

13 ➡ A

The volume *V* of solution to be added is

$$(1500 \text{ ppm}) \times (10{,}000 \text{ ft}^3) + (8000 \text{ ppm}) \times V = (1600 \text{ ppm}) \times (10{,}000 \text{ ft}^3 + V)$$

$$\therefore 1.5 \times 10^7 + 8000V = 1.6 \times 10^7 + 1600V$$

$$\therefore 6400V = 1.0 \times 10^6$$

$$\therefore V = \frac{1.0 \times 10^6}{6400} = \boxed{156 \text{ ft}^3}$$

14 ➡ B

The maximum flux occurs in the center of the spherical reactor, that is, at $r \to 0$. Noting that

$$\lim_{x \to 0} \frac{\sin(kx)}{x} = k$$

we proceed to write

$$\phi_{\max}(r) = \lim_{r \to 0} \phi(r) = \lim_{r \to 0} \left[5 \times 10^{13} \frac{\sin(0.0628r)}{r} \right] = (5 \times 10^{13}) \times 0.0628 = \boxed{3.14 \times 10^{12} \text{ n/cm}^2 \cdot \text{s}}$$

15 ➡ C

The neutron current density is given by the usual relation $J(r) = -Dd\phi(r)/dr$, which in the present case yields

$$J(r) = -0.80 \times \frac{d}{dr}\left[5 \times 10^{13} \frac{\sin(0.0628r)}{r} \right] = -4 \times 10^{13} \left[\frac{0.0628 \cos(0.0628r)}{r} - \frac{\sin(0.0628r)}{r^2} \right]$$

Substituting r = 20 cm,

$$J(r) = -4 \times 10^{13} \times \left[\frac{0.0628 \cos(0.0628 \times 20)}{20} - \frac{\sin(0.0628 \times 20)}{20^2} \right] = \boxed{-5.62 \times 10^{10} \text{ n/cm}^2 \cdot \text{sec}}$$

16 ➡ D

We first compute the fission rate *FR* for a given power Π expressed in MW:

$$FR = \Pi \text{ MW} \times 10^6 \frac{\text{J}}{\text{MW} \cdot \text{s}} \times \frac{1}{1.6 \times 10^{-13}} \frac{\text{MeV}}{\text{J}} \times \frac{1}{200} \frac{\text{fission}}{\text{MeV}} \times \frac{86{,}400}{1} \frac{\text{sec}}{\text{day}}$$

$$\therefore FR = (2.7 \times 10^{21}) \times \Pi \text{ fissions/day}$$

The equation above gives the No. of fissions per day required to yield a power of Π megawatts. The burnup rate *BUR* is obtained with some additional unit conversion:

$$BUR = \left[(2.7 \times 10^{21}) \times \Pi \frac{\text{fissions}}{\text{day}} \right] \times \frac{1 \text{ atom } ^{235}\text{U}}{1 \text{ fission}} \times \frac{235 \text{ g } ^{235}\text{U}}{6.02 \times 10^{23} \text{ atoms } ^{235}\text{U}}$$

$$\therefore BUR = 1.054 \times \Pi \text{ g/day}$$

As it stands, the equation above gives the BUR for a power level Π assuming 100% plant efficiency. For a nonideal facility, we must divide the result above by the plant efficiency η_p,

$$BUR = 1.054 \times \left(\frac{\Pi}{\eta_p} \right) \text{ g/day}$$

so that

$$BUR = 1.054 \times \left(\frac{600}{0.3} \right) = \boxed{2108 \text{ g/day}}$$

17 ➡ D

Plutonium-241 has decay modes γ, β^-, and α. Beta decay yields Am-241:

$$^{241}_{94}\text{Pu} \rightarrow {}^{241}_{95}\text{Am} + {}^{0}_{-1}e^-$$

Alpha decay yields U-237:

$$^{241}_{94}\text{Pu} \rightarrow {}^{237}_{92}\text{U} + {}^{4}_{2}\alpha$$

In turn, krypton-85 beta-decays into Rb-85:

$$^{85}_{36}\text{Kr} \rightarrow {}^{85}_{37}\text{Rb} + {}^{0}_{-1}e^{-1}$$

Thus, rubidium-85 is likely to be building up in the waste sample.

18 ➡ B

The critical equation from modified one-group theory is manipulated to give

$$\frac{k_\infty}{1 + B^2 M_T^2} = 1 \quad \rightarrow \quad k_\infty = 1 + B^2 M_T^2$$

$$\therefore k_\infty = 1 + \left(\frac{\pi}{R} \right)^2 M_T^2$$

$$\therefore k_\infty = 1 + \left(\frac{\pi}{R} \right)^2 \left(L_T^2 + \tau_T \right)$$

$$\therefore k_\infty = 1 + \left(\frac{\pi}{80} \right)^2 \times (8.1 + 27) = \boxed{1.054}$$

19 ➡ B

Given the ratio of moderator-to-fuel atoms N_C/N_U = 450, the resonance integral I_U = 277 b, the epithermal scattering cross-section of carbon $\sigma_{\text{s,epi}}^C$ = 4.66 b, and the logarithmic energy decrement ξ_C = 0.158, we may write

$$p = \exp\left(-\frac{N_F I_F}{\xi_M \Sigma_{\text{s,epi}}^M} \right) = \exp\left(-\frac{N_U I_U}{\xi_C N_C \sigma_{\text{s,epi}}^C} \right)$$

$$\therefore p = \exp\left(-\frac{277}{0.158 \times 450 \times 4.66} \right) = \boxed{0.433}$$

20 ➡ B

Different heat transfer rate terms in a cylindrical fuel pin are such that

$$q = q'H = q'' \times 2\pi RH = q''' \times \pi R^2 H$$

Hence, the heat flux q'' and the power density q''' are related as

$$q'' \times 2\pi RH = q''' \times \pi R^2 H \quad \rightarrow \quad q'' = \frac{\pi R^2 H}{2\pi RH} q'''$$

$$\therefore q'' = \frac{R}{2} q'''$$

$$\therefore q'' = \frac{0.6}{2} \times 500 = \boxed{150 \text{ W/cm}^2}$$

For a temperature difference ΔT_s = 300 – 250 = 50°C, the heat transfer coefficient is

$$h = \frac{q''}{\Delta T_S} = \frac{150}{300 - 250} = \boxed{3.0 \text{ W/cm}^2 \cdot {}^\circ\text{C}}$$

21 ➡ B

The first step is to find the gas constant for the compound in question:

$$R = \frac{\Re}{M} = \frac{8314}{50} = 166.3 \text{ J/kg}\cdot\text{K}$$

The temperature after adiabatic compression is

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = 300\times\left(\frac{0.4}{0.2}\right)^{\frac{1.67-1}{1.67}} = 396.2 \text{ K}$$

Lastly, the work per kg done in the adiabatic compression is

$$W = \frac{R(T_2 - T_1)}{\gamma-1} = \frac{166.3\times(396.2-300)}{1.67-1} = 23{,}900 \text{ J} = \boxed{23.9 \text{ kJ}}$$

22 ➡ B

The temperatures are converted as T_1 = 327°C = 600 K and T_2 = 27°C = 300 K. The heat addition is given by

$$Q_1 = \frac{T_1}{T_1 - T_2}\times W = \frac{600}{600-300}\times 200 = 360 \text{ kJ}$$

The entropy change during heat addition is

$$\Delta S_1 = \frac{Q_1}{T_1} = \frac{360}{600} = \boxed{0.6 \text{ kJ/K}}$$

23 ➡ A

Accounting for the appropriate contributions in the turbine's energy balance, we may write

$$W = \dot{m}\left[h_1 - h_2 + \frac{V_1^2 + V_2^2}{2} + (z_1 - z_2)g\right]$$

$$\therefore W = 20\times\left[3200\times10^3 - 2600\times10^3 + \frac{160^2+100^2}{2} + (10-6)\times9.81\right]$$

$$\therefore W = 1.21568\times10^7 \text{ W} = \boxed{12.1568 \text{ MW}}$$

24 ➡ C

The specific pump work is determined to be

$$W_p = v\Delta p = \frac{1}{\rho}\times(p_1 - p_2) = \frac{1}{1000}\times\left(3.0\times10^6 - 70\times10^3\right) = 2930 \text{ J/kg}$$

$$\therefore \boxed{W_p = 2.93 \text{ kJ/kg}}$$

25 ➡ B

The cost of U_3O_8 is given as $23.20, and one kilogram of U_3O_8 contains a proportion of uranium by mass given by

$$\chi_U \approx \frac{3\times235}{3\times235+8\times16} = 0.8463$$

so that

$$\text{Cost of 1 kg of U} = \$23.20\,\frac{1}{1 \text{ kg } U_3O_8}\times\frac{1}{0.846}\,\frac{\text{kg } U_3O_8}{\text{kg U}} = \boxed{\$27.42}$$

26 ➡ C

Firstly, for the feed-product ratio using natural uranium feed ($x_f \approx 0.711$), we may write

$$\frac{F}{P} = \frac{x_p - x_w}{x_f - x_w} = \frac{3.2-0.4}{0.711-0.4} = 9.003$$

The cost of one kg of uranium was determined in the previous problem and equals $27.42. The cost of fuel product, accounting for the $5.40 needed for chemical conversion, is then

$$\text{Cost of 1 kg product} = 9.003\,\frac{\text{kg-feed}}{\text{kg-prod}}\times\frac{(\$27.42+\$5.40)}{\text{kg U}} = \$295.48\text{/kg of product}$$

Next, to determine the SWU cost, we first compute the value functions

$$V_p = (2x_p - 1)\ln\left(\frac{x_p}{1-x_p}\right) = (2\times 0.032 - 1)\times \ln\left(\frac{0.032}{1-0.032}\right) = 3.191$$

$$V_w = (2\times 0.004 - 1)\times \ln\left(\frac{0.004}{1-0.004}\right) = 5.473$$

$$V_f = (2\times 0.00711 - 1)\times \ln\left(\frac{0.00711}{1-0.00711}\right) = 4.869$$

Then, using the separative work equation,

$$\frac{S}{P} = V_p - V_w - \frac{F}{P}(V_f - V_w) = 3.191 - 5.473 - 9.003\times(4.869 - 5.473)$$

$$\therefore \frac{S}{P} = 3.156$$

Finally, the total cost for 24,600 kilograms of U in a batch is

$$\text{Cost} = \text{Batch size}\times\left[(\text{Product cost}) + \frac{S}{P}\times(\text{SWU cost}) + (\text{Fabrication cost})\right]$$

$$\therefore \text{Cost} = 24{,}600\times(\$295.48 + 3.156\times\$98 + \$220) = \boxed{\$20{,}290{,}000}$$

27 ➡ C

The availability factor is given by the ratio of the period during which the reactor was operational (= 9 months) to the total period considered (= 12 mo):

$$AF = \frac{9\text{ months}}{12\text{ months}} = \boxed{0.75}$$

28 ➡ A

The capacity factor is given by the relationship

$$CF = \int_0^T \frac{P(t)}{P_R T}dt$$

where t is time, T is the full period of observation (usually one year), and P_R is the electrical power rating of the reactor. With reference to the given graph, we may write

$$CF = \int_0^T \frac{P(t)}{P_R T}dt = \frac{1}{800\text{ MW}\times 1\text{ yr}}\left[\begin{array}{c}(0.8\times 800)\times 0.25 + (0\times 800)\times 0.25 \\ +(1.0\times 800)\times 0.25 + (0.6\times 800)\times 0.25\end{array}\right]$$

$$\therefore \boxed{CF = 0.55}$$

29 ➡ A

A 0.3% change represents a decimal reactivity change of 0.003. A dollar of reactivity is defined as the amount of reactivity necessary to take a reactor 'prompt critical' (that is, critical to prompt neutrons alone). In equation form, this means that $\rho = \beta$, where ρ is reactivity and β is the delayed neutron fraction (i.e., the fraction of all neutrons born delayed). For a U-235 fueled reactor, $\beta \approx 0.0065$, hence the given reactivity in cents is

$$\rho = \frac{0.003}{0.0065} = 0.462\text{ dollars} = \boxed{46.2\text{ cents}}$$

30 ➡ D

The worth of a partially inserted rod can be estimated with the equation

$$\rho_\omega(x) = \rho_\omega(H)\left[\frac{x}{H} - \frac{1}{2\pi}\sin\left(\frac{2\pi x}{H}\right)\right]$$

Noting that $\rho_\omega(H)$ = 50 cents, the worth associated with $x = 3H/4$ is

$$\rho_\omega\left(\frac{3H}{4}\right) = 50\times\left[\frac{3\cancel{H}/4}{\cancel{H}} - \frac{1}{2\pi}\sin\left(\frac{2\pi\times 3\cancel{H}/4}{\cancel{H}}\right)\right] = \boxed{45.5\text{ cents}}$$

31 ➡ C

The power Π rises exponentially with time and has a period T = 10 minutes; mathematically,

$$\Pi(t) = \Pi_0 \exp(t/T) \quad \rightarrow \quad 10^6 = 10^{-3}\exp(t/10)$$
$$\therefore 10^9 = \exp(t/10)$$
$$\therefore \ln 10^9 = \frac{t}{10}$$
$$\therefore t = 10 \times \ln 10^9 = \boxed{207\text{ min}}$$

The power level will reach 1 MW within three hours and 27 minutes.

32 ➡ A

For a ^{235}U-fueled reactor, 5 dollars of negative reactivity amount to ρ = −5 × 0.0065 = −0.0325. This added reactivity will cause the power to drop to a level P_J such that

$$P_J = \frac{\beta(1-\rho)}{\beta-\rho}P_0 = \frac{0.0065\times(1+0.0325)}{0.0065+0.0325}\times 1.0 = 0.172\text{ MW}$$

Upon being lowered to 0.172 MW, the power decreases further according to the exponential law

$$P(t) = P_J\exp\left(-\frac{t}{80}\right) = 0.172\times 10^6\exp\left(-\frac{t}{80}\right)$$

(T = 80 sec is the usual period for negative reactivity insertions.) The time T_0 required for the power to drop to 1 mW = 10^{-3} W is determined as

$$P(T_0) = 10^{-3} = 0.172\times 10^6 \exp\left(-\frac{T_0}{80}\right)$$
$$\therefore \frac{10^{-3}}{0.172\times 10^6} = \exp\left(-\frac{T_0}{80}\right)$$
$$\therefore \ln\left(\frac{10^{-3}}{0.172\times 10^6}\right) = -\frac{T_0}{80}$$
$$\therefore T_0 = -80\times\ln\left(\frac{10^{-3}}{0.172\times 10^6}\right) = 1517\text{ sec} = \boxed{25.3\text{ min}}$$

The power will drop to 1 mW within less than half an hour.

33 ➡ B

→ Surface barrier detectors are used for alpha spectrometry;
→ Bismuth germanate is a gamma-ray detector;
→ Proton recoil detectors measure fast neutrons;
→ Plastic scintillators are used for electron spectrometry;

34 ➡ C

Following the problem statement, the count measurement process is Poisson-distributed with rate parameter λ = 2 × 1.21 = 2.42 counts. In order to determine the probability that at least one count will be recorded, we subtract the probability of 0 counts being recorded from 1:

$$\Pr(n>0) = 1 - \Pr(n=0) = 1 - \left.\left(\frac{e^{-\lambda}\lambda^n}{n!}\right)\right|_{n=0}$$
$$\therefore \Pr(n>0) = 1 - \frac{e^{-2.42}\times 2.42^0}{0!} = \boxed{0.911}$$

35 ➡ B

Firstly, the energy of a scintillation photon is given by Planck's law:

$$E = h\nu = \frac{hc}{\lambda} = \frac{(4.14\times 10^{-15})\times(3.0\times 10^8)}{447\times 10^{-9}} = 2.78\text{ eV}$$

The total energy afforded by 32,000 such photons is 32,000 × 2.78 = 88,960 eV. Dividing this by the input energy deposition (= 1 MeV) gives the scintillation efficiency η_S:

$$\eta_s = \frac{88{,}960\ \text{eV}}{10^6\ \text{eV}} \times 100\% \approx \boxed{8.90\%}$$

36 ➡ D

The first step is to ascertain the density of free air, which equals ~0.00129 g/cm^3 at 273 K and 760 torr:

$$\rho = 0.00129 \times \left(\frac{273}{298}\right) \times \left(\frac{780}{760}\right) = 0.00121\ \text{g/cm}^3$$

The entrance port area is

$$A = \pi r^2 = \pi \times 0.2^2 = 0.126\ \text{cm}^2$$

Finally, the total exposure measured in this event is

$$E_p = \frac{\dot{q}\Delta t}{\rho A L} = \frac{\left(0.3\times 10^{-9}\right)\times 80}{0.00121 \times 0.126 \times 5.0} = 3.15\times 10^{-5}\ \text{C/g}$$

$$\therefore E_p = 3.15\times 10^{-5}\ \frac{\text{C}}{\text{g}} \times \frac{1}{2.58\times 10^{-7}}\ \frac{\text{R}}{\text{C/g}} = \boxed{122\ \text{R}}$$

37 ➡ C

The ratio of the activity of source B to source A is given by

$$\text{Ratio} = \frac{\left(\text{Source B + background count rate}\right) - \left(\text{background count rate}\right)}{\left(\text{Source A + background count rate}\right) - \left(\text{background count rate}\right)}$$

Let *c* and *t* denote the number of counts and measurement time, respectively. Further, let subscript *b* denote 'background', *bb* denote 'source B + background', and *ab* denote 'source A + background'. With these notations in mind, we proceed to write

$$\text{Ratio} = \frac{\dfrac{c_{bb}}{t_{bb}} - \dfrac{c_b}{t_b}}{\dfrac{c_{ab}}{t_{ab}} - \dfrac{c_b}{t_b}} = \frac{717/2 - 51/10}{251/5 - 51/10} = \boxed{7.84}$$

38 ➡ C

We first write down the governing equations for both nonparalyzable counters:

$$\begin{cases} n - m_A = n m_A \tau_A & \text{(I)} \\ n - m_B = n m_B \tau_B & \text{(II)} \end{cases}$$

But, per the problem statement, $m_B\tau_B = 2m_A\tau_A$. Substituting into (II),

$$\begin{cases} n - m_A = n m_A \tau_A & \text{(I)} \\ n - \dfrac{2\tau_A m_A}{\tau_B} = 2n m_A \tau_A & \text{(III)} \end{cases}$$

The system comprised by equations (I) and (III) has the trivial solution $n = 0$, which is useless in the present problem, and the meaningful solution

$$n = \frac{\tau_B - 2\tau_A}{\tau_A \tau_B}$$

so that, with τ_A = 30 μs and τ_B = 100 μs, we obtain

$$n = \frac{(100 - 2\times 30)\times 10^{-6}}{\left(30\times 100\right)\times 10^{-12}} = \boxed{13{,}300\ \text{sec}^{-1}}$$

39 ➡ D

According to Osif *et al.* (2004):

> *During the 10-day period over which the* [Three Mile Island] *accident occurred, the residents of the TMI area received doses primarily from a radioactive isotope of xenon (xenon-133) and, to a lesser extent, from krypton-85. An estimated ten million curies of xenon were released. Trace amounts of radioactive iodine (thirty*

curies of iodine-131 and four curies of iodine-133) were also released. Both were released into the atmosphere as radioactive gases escaped from the damaged reactor.

40 ➡ C

→ The Fukushima Daiichi reactors were GE boiling water reactors supplied by GE itself, Toshiba, and Hitachi. Thus, statement (A) is correct.
→ Hydrogen explosions were found to contribute to reactor damage in Fukushima Daiichi Units 1 and 3, and possibly also in Unit 2, but played no role in the much milder situation at nearby Fukushima Daini plant. Thus, statement (B) is correct.
→ Japan's Nuclear and Industrial Safety Agency originally placed the situation in Daiichi units 1 to 3 as level 5 in the INES. However, a month after the tsunami, the agency actually *increased* the rating to level 7, the most severe scale, as a re-evaluation of early radioactive releases suggested that some 630 PBq of iodine-131 equivalent had been discharged, thereby matching the criterion for INES 7. Thus, statement (C) is false.
→ TEPCO and other authorities reported no exposure to radiation severe enough to induce acute illness (let alone death), although long-term effects are still being debated. Thus, statement (D) is correct.

REFERENCES

- BOGARD, J.S., DOWNING, D.J., COLEMAN, R.L. *et al.* (2007). *Atoms, Radiation, and Radiation Protection*. 3rd edition. Wiley-VCH.
- KNOLL, G.F. (2010). *Radiation Detection and Measurement*. 4th edition. John Wiley and Sons.
- LAMARSH, J.R. and BARATTA, A.J. (2001). *Introduction to Nuclear Engineering*. 3rd edition. Prentice-Hall. **(Recommended book!)**
- LEWIS, E.E. (2008). *Fundamentals of Nuclear Reactor Physics*. Academic Press. **(Recommended book!)**
- MARTIN, A., HARBISON, S., BEACH, K. and COLE, P. (2012). *An Introduction to Radiation Protection*. 6th edition. Hodder Education.
- MURRAY, R.L. and HOLBERT, K.E. (2015). *Nuclear Energy*. 7th edition. Butterworth-Heinemann. **(Recommended book!)**
- OSIF, B.A., BARATTA, A.J. and CONKLING, T.W. (2004). *TMI 25 Years Later: The Three Mile Island Nuclear Power Plant Accident and its Impact*. Pennsylvania State University Press.
- PODGORSAK, E.B. (2014). *Compendium to Radiation Physics for Medical Physicists*. Springer.
- SHULTIS, J.K. and FAW, R.E. (2017). *Nuclear Science and Engineering*. 3rd edition. CRC Press.
- TAMRAKAR, A.K. and HARURSAMPATH, D. (2014). *Wiley Acing the GATE – Mechanical Engineering*. Wiley India.