This exam comprises 4 problems. The total number of points is 50. The final grade is obtained by dividing the number of points by 5.

Don't forget to write your name and student number (also on the separate sheet).

Problem 1 (14 pts)
Answer the following questions briefly (1 to 2 sentences).

a. Why is the large majority of fission nuclear reactors called thermal reactors? (2 pts)
b. Give an example of an industrial application of nuclear cogeneration. (2 pts)
c. Why do you need to add a fissile driver to thorium (to use thorium as fuel in a reactor)? (2 pts)
d. Why is the reaction $n + {}^{235}_{92}U \rightarrow {}^{118}_{46}Pd + {}^{118}_{46}Pd$ an unrealistic one for a fission reactor? (2 pts)
e. Why don't breeder reactors use a moderator? (2 pts)
f. What is the difference between an open fuel cycle and a closed one for a fission reactor? (2 pts)
g. Which main elements are recovered from the reprocessing of spent fuel? (2 pts)

Solution

a. The majority of fission reactors are thermal reactors, as the fission cross section is largest for thermal neutrons.
b. For example, desalination and district heating
c. Thorium cannot sustain a chain reaction on its own, therefore fissile material needs to be added to thorium.
d. The reaction is symmetric and there are no neutrons emitted.
e. Breeder reactors are fast reactors, therefore using fast neutrons, so we don't want to slow the neutrons down.
f. An open fuel cycle treats the spent fuel as waste, while in a closed one, the spent fuel is recycled and new fuel is fabricated.
g. The reprocessing of spent fuel recovers isotopes of uranium and plutonium.

Problem 2 (12 pts)

Xenon-135 is a neutron poison that results from the beta decay of Iodine-135. The half-lives of I-135 and Xe-135 are $T_{1/2} = 6.55\ h$ and $T_{1/2} = 9.168\ h$, respectively.

The rate of change in iodine concentration is given by

$$\frac{dN_I}{dt} = \gamma_I \Sigma_f^{fuel} \phi - \lambda_I N_I$$

And the rate of change in xenon concentration by

$$\frac{dN_{Xe}}{dt} = \gamma_{Xe} \Sigma_f^{fuel} \phi + \lambda_I N_I - \lambda_{Xe} N_{Xe} - \sigma_a^{Xe} N_{Xe} \phi$$

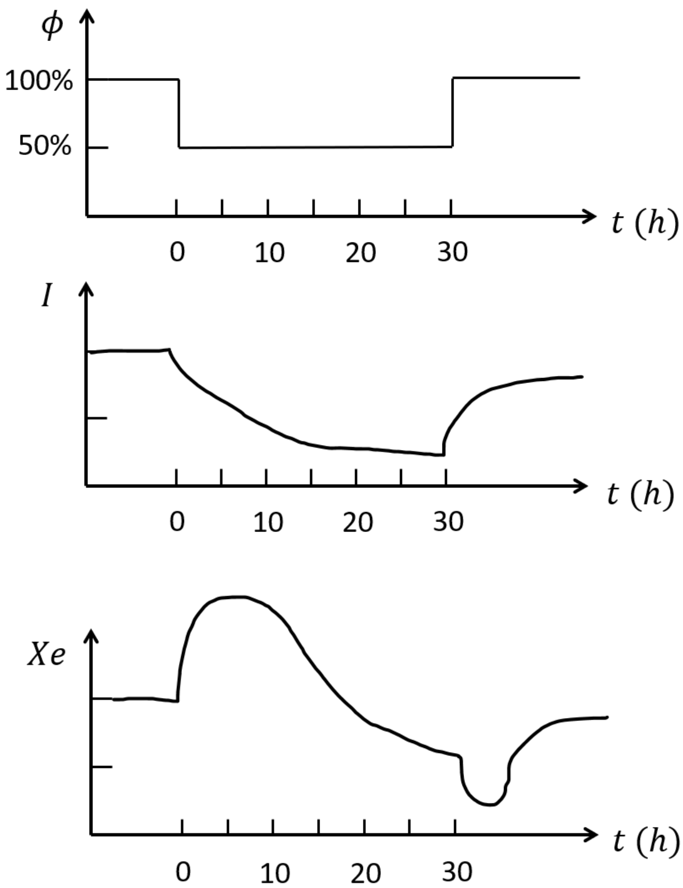
a. The term $\gamma_{Xe}\Sigma_f^{fuel}\phi$ on the right-hand side of the equation dN_{Xe}/dt corresponds to the production of Xe-135 from fission. Give the meaning of the other three terms. (6 pts)

b. The concentrations of I-135 and Xe-135 depend on the variations of the neutron flux. Use the extra paper to draw the concentrations of iodine and xenon as a function of time. Assume that the reactor has been operated long enough for the concentrations to have reached equilibrium. (6 pts)

Solution

a. The term $\lambda_I N_I$ corresponds to the production of Xe-135 from the decay of I-135. The term $\lambda_{Xe}N_{Xe}$ represents the radioactive decay of Xe-135 and the term $\sigma_a^{Xe}N_{Xe}\phi$ is the burnup of xenon by neutrons. The last two terms have a minus sign, as these correspond to a loss of xenon.

b. Since we assume that the reactor has been operated long enough for the concentrations of I and Xe to have reached equilibrium, the first part of both graphs is a flat line.
At $t = 0$, the neutron flux decreases and the concentration of I decreases exponentially until $t = 30\ h$. In contrast, the Xe concentration increases as its half-life is longer than that of I. The maximum occurs at around $t = 10\ h$. With the neutron flux decreasing, the burnup of Xe is also decreasing.
At $t = 30\ h$, the flux increases to its previous level. The concentration is I grows exponentially until it reaches the same equilibrium value as the one before $t = 0\ h$. The increase of the neutron flux causes the burnup of Xe to increases and results in a dip in the concentration. The Xe concentration then increases back to its previous equilibrium value.



Problem 3 (16 pts)

a. Explain briefly how the toroidal and poloidal magnetic fields are generated in a tokamak. (4 pts)

b. The breeding of tritium is a crucial part of a fusion reactor. At present, tritium is envisaged to be produced through reactions between lithium and neutrons.
The reaction ${}^{6}_{3}Li + n \rightarrow {}^{4}_{2}He + {}^{3}_{1}H$ is exothermic, while the reaction ${}^{7}_{3}Li + n_{fast} \longrightarrow {}^{4}_{2}He + {}^{3}_{1}H + n$ is endothermic.

Calculate the minimum kinetic energy that the incident neutron (n_{fast}) must have for the reaction with ${}^{7}_{3}Li$ to take place. (4 pts)

c. Why it is crucial to stop neutrons in the blanket of a fusion reactor? (4 pts)

d. What are the main differences between a tokamak and a stellarator. (4 pts)

Element	n	${}^{3}_{1}H$	${}^{4}_{2}He$	${}^{7}_{3}Li$
Mass excess (keV)	8071.6181	14949.8109	2424.91587	14907.105

Solution

a. The toroidal magnetic field is generated by the toroidal coils around the tokamak, while the poloidal field is induced by a current in the plasma produced by the solenoid.
b. The Q-value of the reaction is

$$Q = (8071.6181 + 14907.105) - (2424.91587 + 14949.8109 + 8071.6181)$$

$$Q = -2467.6 \, keV$$

This result indicate that the incident neutron must have an energy of at least $2467.6 \, keV$.

c. To increase the efficiency of producing electricity, we want to capture most of the neutron heat. Neutrons transfer their heat colliding with the material, progressively slowing down. To protect the superconductors: if not stopped, neutrons risk to damage or heat the magnets behind the blanket. To be superconductive, magnets must stay cool. And to eventually breed tritium.
d. The differences between a tokamak and a stellarator are: first of all, the shape of the plasma, the fact that the poloidal field is created by coils in stellarator and not by a current. In addition, the tokamak is a pulsed machine, while the stellarator can be operated continuously.

Problem 4 (8 pts)

Congratulations! You've won billions at the lottery. You never need to work anymore. However, you are thinking about contributing to the fight against climate change and donate money to the research and development of clean energy sources.
What are your plans? Justify your choices. **One page maximum!**

Q-value of the reaction $1 + 2 \to 3 + 4 + \cdots$

$$Q = (M_1 + M_2) - (M_3 + M_4 + \cdots)$$

Activity:

$$A = \lambda N = \lambda N_0 e^{-\lambda t}$$

Half-life:

$$\frac{N\left(t + T_{1/2}\right)}{N(t)} \equiv \frac{1}{2}$$