NUCLEAR ENERGY EXAM 31-10-2017 from 18:30 to 21:30

Name and student number must be on each sheet handed in.

Problem 1 (10 pts)

a. Calculate the binding energy per nucleon of ^{236}U (Z= 92). (2 pts)

B = 92 x 1.007825 + 144 x 1.008665 – 236.045568 = 1.922092 u = 1790.42 MeV

B/A = 1790.42/236 = 7.58 MeV/nucleon ≈ 7.6 MeV/nucleon

b. The binding energy of stable nuclei between A = 75 and A = 160 is 8.5 MeV/nucleon. Calculate the energy released by the fission of ^{236}U into two fragments in the A = 75-160 mass region. (2 pts)

B/A(fragments) – B/A(236U) = 8.5 – 7.6 = 0.9 MeV/nucleon → E = 0.9*236 = 212.4 MeV

c. Calculate the energy released by the reaction $^{235}_{92}U + n \rightarrow {}^{136}_{52}Te + {}^{97}_{40}Zr + 3n$. (2 pts)

Q = 182.15 MeV

d. Compare the energies obtained in b. and c. Explain why the values are different. (4 pts)

The Q-value from c. contains the energy released by the fission fragments and prompt neutrons. However, it is missing the kinetic energy contributions from the prompt γ-rays, the decay of the fission fragments (which includes β-decay electrons, antineutrinos and γ-rays). The energy released in b. contains all kinetic energies mentioned above, since we take the binding energy of STABLE fragments into account. **The average energy released by fission is about 200 MeV.**

Problem 2 (10 pts)

In a reactor, ^{135}Xe is produced directly by fission and as a decay product of the ^{135}Te decay chain:

$^{135}_{52}Te \xrightarrow{\beta^-} {}^{135}_{53}I \xrightarrow{\beta^-} {}^{135}_{54}Xe \xrightarrow{\beta^-} {}^{135}_{55}Cs \xrightarrow{\beta^-} {}^{135}_{56}Ba$ (stable).

The half-life of each isotope is: $T_{1/2}(^{135}Te)$ = 19 seconds, $T_{1/2}(^{135}I)$ = 6.57 hours, $T_{1/2}(^{135}Xe)$ = 9.1 hours, $T_{1/2}(^{135}Cs)$ = 2.3 x 10^6 years.

The rate of change of the ^{135}I concentration during the operation of a reactor is

$$\frac{dN_I}{dt} = \gamma_I \Sigma_f^{Fuel} \phi - \lambda_I N_I - \sigma_{abs}^{I} N_I \phi .$$

a. Each term in the equation above corresponds to a specific physical process. Describe each term. (2 pts)

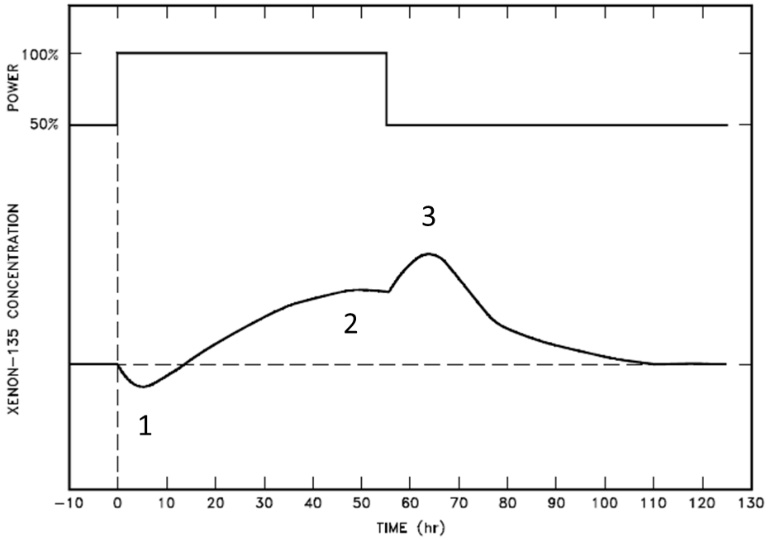
I produced by fission – radioactive decay of I – burn up of I through neutron absorption

b. Why isn't there a contribution from ^{135}Te? (1 pt)

The half-life of ^{135}Te is very short compared to that of ^{135}I, therefore we can make the assumption that ^{135}I is created directly by fission.

c. Write the differential equation of the rate of change of the ^{135}Xe concentration. (2 pts)

$$\boxed{\frac{dN_{Xe}}{dt} = \gamma_{Xe}\,\Sigma_f^{Fuel}\phi + \lambda_I\, N_I - \lambda_{Xe}\, N_{Xe} - \sigma_{abs}^{Xe}\, N_{Xe}\,\phi}$$



d. The picture above shows the reactor power and the corresponding ^{135}Xe concentration as a function of time. Describe the behaviour of ^{135}Xe in the regions labelled 1 (sudden increase in reactor power), 2 (constant reactor power) and 3 (sudden decrease of reactor power). (5 pts)

Region 1: The burnup of Xenon increases due the increase of neutron flux.
Region 2: The Xenon concentration reaches equilibrium.
Region 3: Iodine decays faster than Xenon, therefore there is a build-up of Xenon.

Problem 3 (10 pts)

a. Assume that the effective multiplication factor k_{eff} remains constant from generation to generation and N_0 is the initial number of neutrons. Determine the number of neutrons N_n after n generations. (2 pts)

$$\boxed{\begin{aligned} & k_{eff} = \frac{N_1}{N_0}; k_{eff} = \frac{N_2}{N_1} = \frac{N_2}{N_0 k_{eff}}; \\ & N_5 = k \times k \times k \times k \times k \times N_0 \\ & N_n = k^n N_0 \end{aligned}}$$

b. Assume that 10000 neutrons exist at the beginning of a generation. Given the values for each factor in the six-factor formula, calculate the number of neutrons that exist at the points in the neutron life cycle listed below: (6 pts)

1. Number of neutrons that exist after fast fission = 10000 x ε = 10310
2. Number of neutrons that start to slow down in the reactor =
   10000 x ε x P_{FNL} = 9165.6
3. Number of neutrons that reach thermal energies = 10000 x ε x P_{FNL} x p = 7360
4. Number of neutrons that are absorbed in the reactor =
   10000 x ε x P_{FNL} x p x P_{TNL} = 6661
5. Number of neutrons that are produced from thermal fission
   = 10000 x ε x P_{FNL} x p x P_{TNL} x f x η = 10065

$\varepsilon = 1.031$ $P_{FNL} = 0.889$ $P_{TNL} = 0.905$ $p = 0.803$ $\eta = 2.012$ $f = 0.751$

c. Explain the effect of a rise in temperature in the reactor core on p. (2 pts)

With rising temperature, the coolant expands and the density of moderator decreases. The neutrons travel further, which increases the probability of a fast neutron to be absorbed. This translates in a decrease in the resonance escape probability p.

Problem 4 (10 pts)

a. The ITER project has five main goals. Which two do you consider most important or challenging? (2 pts)

Personal choice out of:

1) Produce 500 MW of fusion power for pulses of 400 s

2) Demonstrate the integrated operation of technologies for a fusion power plant

3) Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating.

4) Test tritium breeding

5) Demonstrate the safety characteristics of a fusion device

b. Natural lithium has two stable isotopes ${}^{6}Li$ (7.5%) and ${}^{7}Li$ (92.5%). Both can be used to breed tritium (${}^{3}H$) to fuel ITER via the two reactions: ① ${}^{6}_{3}Li + n_{slow} \rightarrow {}^{4}_{2}He + {}^{3}_{1}H$ and ② ${}^{7}_{3}Li + n_{fast} \rightarrow {}^{4}_{2}He + {}^{3}_{1}H + n'$. Calculate the Q-value of each reaction. (2 pts)

Q_1 = 4.78 MeV

Q_2 = -2.47 MeV

c. What is the minimum kinetic energy that the fast neutron should have for the reaction with ${}^{7}Li$ to take place? (2 pts)

2.47 MeV

d. Describe the possible fates of the neutron (n'), released in equation ②, as a function of its energy (high and low). (4 pts)

If the neutron has an energy larger than 2.47 MeV it can react with ${}^{7}Li$, i.e. more tritium and more neutrons produced. The latter, depending on their energy, can react with Li via reaction 1 or 2.

If the neutron energy is below the threshold (E< 2.47 MeV), the neutron can react with ${}^{6}Li$ and produce tritium.

M(H) = 1.007825 u

M(n) = 1.008665 u

M(${}^{236}U$) = 236.045568 u

M(${}^{6}Li$) = 6.015122 u

M(${}^{4}He$) = 4.002603 u

M(${}^{235}U$) = 235.043929 u

M(${}^{136}Te$) = 135.920100 u

M(${}^{97}Zr$) = 96.910953 u

M(${}^{7}Li$) = 7.016004 u

M(${}^{3}H$) = 3.016049 u

1 u = 931.494 MeV/c^2