TENTAMEN *NUCLEAR ENERGY* (NAKE-12)

01-11-2016 18.30-21.30 A.Jacobshal

- this exam consists of 4 questions
- value of the questions 1-4: 2, 2, 2.5, 2.5

  (1 point is "for free")
- the weight of the subquestions is the same
- **please use a separate sheet of paper for each question !!**
- write your name and studentnumber on each sheet of paper you hand in
- motivate your answers and give the formulas on which your numerical answers are based

1. General question

a) Answer the following 3 questions for each type of nuclear reactor:

PWR, BWR, CANDU, HTGR, fast breeder reactor, RBMK (Chernobyl-type).

a1) which type of fuel is used (include enrichment factor)

a2) what material is the cooling medium

a3) what material is the moderator

b) What are the main properties of moderator materials?

c) Why are fission fragments radioactive? Which forms of radioactivity do fission fragments show?

d) What is de role of neutrons emitted by the fission fragments in a nuclear reactor?

e) In a uranium mine in Gabon (Africa) a natural nuclear reactor has been operating 1.7×10^9 years ago. How do we know this? What made the operation of this reactor possible?

Given: the halflife of ^{235}U is 704×10^6 years.

2. Time dependent behaviour

a) What is the difference between "prompt" and "delayed" neutrons?

b) The so-called reactivity is defined as: $\rho = (k-1)/k$

Consider the increase of the number of neutrons dn produced by the fission process during a certain timeperiod dt.

Until time t=0, the reactor is operating stationary. At t=0, a disturbance occurs, resulting in a change of ρ. Derive an expression for dn/dt after a this disturbance, introducing a "neutron lifetime" T.

c) Solve this equation (question b) for the number of neutrons n

Assume now (for questions d and e) a typical neutron lifetime in a reactor of 100 μs, and a disturbance $\rho = 0.001$.

d) By what factor is the number of neutrons increased after 1 ms ?

e) By what factor is the number of neutrons increased after 1 s ?

f) Based on the previous question, what do you conclude for operation of the reactor ?

3. Accelerator driven sub-critical reactor

Accelerator driven sub-critical reactors are being considered as an interesting option for the transmutation of nuclear waste and more in particular for the "burning" of "minor" actinides (isotopes of among others Am and Cm) produced in power reactors.

a) What are the main reasons to choose a sub-critical reactor to "burn" the "minor" actinides rather than adding them to the fuel of a "normal", critical reactor.
b) How does the steady-state fission rate F [fissions/s] in an accelerator driven sub-critical reactor depend on the intensity of the particle beam from the accelerator for a given, constant value of the multiplication factor k. Motivate your answer.
c) Given the multiplication factor k, which fraction of the neutrons and of the fission rate in a sub-critical reactor is produced by the particle beam from the accelerator in the steady state. Motivate your answer.
d) What happens with the fission rate when the beam from the accelerator is switched off. How does the timeconstant of this process depend on the multiplication factor k.

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4. Plutonium batteries in space

NASA uses Radio-isotope Thermoelectric Generators (RTG's) to power deep space missions like Voyager and Curiosity. In a RTG the heat produced in the decay of ^{238}Pu is converted into electricity.

Consider a RTG that contains 5 kg of plutonium dioxide ($^{238}PuO_2$) and that converses thermal power to electric power with a 5% efficiency.

a) Show that the total activity of the ^{238}Pu in the RTG is equal to $2.8 \cdot 10^{15}$ Bq $= 2.8$ PBq.
b) Calculate the electric power (in Watt) of the RTG.
c) Estimate the dose rate at 2 m distance of the RTG by assuming that the ^{238}Pu can be considered as a point source with no shielding.
d) Normally, the ^{238}Pu in a RTG is shielded by steel. Calculate the thickness of steel needed to reduce the dose rate at 2 m distance to 0.1 mSv h^{-1}. Assume that the build-up factor is 100.

During a failed launch of a space craft powered by the RTG it burns in the earth's atmosphere. The complete inventory of $^{238}PuO_2$ falls homogeneously on a surface of 10000 km^2.

e) Calculate the effective dose if a person would inhale 0.1% of the plutonium dioxide that is present on a surface of 1 square meter. How does this dose compare to the dose a person receives due to natural radiation in the Netherlands?

Data that can be used:

^{238}Pu decays (half life 87.7 year) by emission of an α-particle to the ground state and two exited states of ^{234}U (half life $2.4 \cdot 10^5$ year). The Q-value of this decay (to the ground state) is 5.59 MeV. The two excited states immediately decay to the ground state of ^{234}U with the emission of two low energy gamma rays (43 and 100 keV).
Γ: specific gamma-ray dose constant (at 1 m) for ^{238}Pb: $2 \cdot 10^{-6}$ mSv m^2 h^{-1} MBq^{-1}.
μ: effective linear attenuation coefficient of steel for gamma radiation of ^{238}Pu: 10 cm^{-1}.
$e_{inh}(50)$: effective dose coefficient for the inhalation of ^{238}Pu: $1.5 \cdot 10^{-5}$ Sv Bq^{-1}.