General information

The exercise sessions will be held as blackboard sessions, where the participants will present their solutions to the group. As such, the problems should be set up and solved before the session. The focus of the exercises lies on analyzing and discussing the task at hand together with the group: thus, a perfect solution is not required to be awarded points. A point will be awarded for each question, and a person will be chosen to present their solution from the pool.

Exercise 1.

Deuterium-Tritium Fusion

a) Explain why deuterium (D) and tritium (T) is expected to be used as fuel for fusion reactors compared to other species (H, He-3, Li, B, etc).

b) In the context of the fusion reaction, what are the challenges for D-T?

c) Provide examples of fusion reactions that are immune to or less affected by the challenges previously mentioned. Explain the difficulty in using these reactions.

Solution 1.

a) Deuterium-Tritium fusion reaction has the highest cross-section in the temperature range achievable with immediate technologies (immediate as in available now or currently being demonstrated).

b) D-T fusion requires tritium which has a negligible concentration in nature and thus poses a self-sufficiency problem. Tritium is also radioactive. D-T fusion also generates high-energy neutrons, and together with tritium, poses a nuclear safety problem.

c) Two reaction examples:

- $^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + 2\text{p}$
- $\text{p} + {}^{11}\text{B} \rightarrow 3\,{}^{4}\text{He}$

Both the reactant and products of these reactions are stable. These reactions also do not produce neutrons. ^{3}He is not easily accesible on Earth and thus suffers the same self-sufficiency issue as tritium. Both of these reactions have rates that are much smaller than D-T in achievable temperatures. For the same fusion power output, a much higher temperature is required. The higher charge states of ^{3}He and ^{11}B also increase the Bremmsstrahlung losses.

Exercise 2.
Tritium self-sufficiency

a) List the natural and artificial sources of tritium and their estimated inventory/production rates.

b) Show that the energy released in deuterium-tritium (D-T) fusion is 17.6 MeV

$$\mathrm{D} + \mathrm{T} \rightarrow {}^{4}\mathrm{He} + \mathrm{n}$$

c) Calculate the consumption rate of tritium per year for 1 GW of fusion power. Assume full continuous operation. How does this compare to the world tritium inventory?

Solution 2.
a)

- interaction between cosmic rays and earth's atmosphere (order of g to kg per year)
- nuclear weapon testing between 1945-1980 (few dozen kgs dissolved in oceans)
- existing nuclear weapons (few g per warhead)
- CANDU fission reactors (130g per year per reactor)

b) According to $E = mc^2$ the energy released can be related to the mass change:

$$\Delta \mathrm{E} = \Delta \mathrm{mc}^2,$$

where Δm is the mass change between the products and the reactants.

$$\Delta m_{D-T} = (m_D - m_T) - (m_{He-4} + n) = (2.0141\ \mathrm{u} + 3.0160\ \mathrm{u}) - (4.0026\ \mathrm{u} + 1.0086\ \mathrm{u}) = \\ = 1.89 \times 10^{-2}\ \mathrm{u} = 3.138 \times 10^{-29}\ \mathrm{kg}$$

and thus

$$\Delta E_{D-T} = 3.138 \times 10^{-29}\ \mathrm{kg}(3 \times 10^8)^2 = 2.825 \times 10^{-12}\ \mathrm{J} \approx 17.6\ \mathrm{MeV}$$

c) Using $\Delta E_{D-T} = 2.825 \times 10^{-12}$ J, the amount of fusion reaction per second for 1 GW of fusion power is:

$$\begin{aligned} S_{D-T} &= \frac{P_{fus}}{\Delta E_{D-T}} \\ &= \frac{10^9}{2.825 \times 10^{-12}} \\ &= 3.54 \times 10^{20}\ \mathrm{s}^{-1} \end{aligned}$$

For each fusion reaction, 1 tritium atom of mass $m_T = 3.016$ amu is consumed, giving a mass consumption rate of

$$\begin{aligned} \Gamma_T &= S_{D-T} m_T \\ &= 3.54 \times 10^{20} \cdot 3.016 \cdot 1.66 \times 10^{-27} \\ &= 1.77 \times 10^{-6}\ \mathrm{kg\ s}^{-1} \end{aligned}$$

For a continuous operation:

$$\begin{aligned} \Gamma_T/\mathrm{yr} &= 1.77 \times 10^{-6} \times 3600 \times 24 \times 365 \\ &= 56.0678\ \mathrm{kg\ yr}^{-1} \approx 56\ \mathrm{kg\ yr}^{-1} \end{aligned}$$

This is higher than the current projected world tritium inventory from CANDU reactors (30-45 kg)

Exercise 3.

Tritium is a radioactive isotope of hydrogen with $T_{\frac{1}{2}} = 12.32$ a, making its natural abundance small. Instead, tritium can be bred from lithium according to

$$\begin{aligned} &{}^6\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \mathrm{T} + 4.8\ \mathrm{MeV}\ (7.5\%), \\ &{}^7\mathrm{Li} + \mathrm{n} \rightarrow {}^4\mathrm{He} + \mathrm{T} + \mathrm{n} - 2.5\ \mathrm{MeV}\ (92.5\%), \end{aligned}$$

where the parentheses refers to the natural occurrence of the isotopes.

a) Show how fusion reactors can utilize lithium as a tritium source.

b) What is the fundamental challenge in generating tritium in a fusion reactor?

c) What can be done to overcome this challenge?

d) What are the main considerations in designing tritium generation technologies?

Solution 3.

a) A blanket region consisting of lithium position between the plasma and the vacuum vessel wall captures fusion neutrons producing tritium. The tritium is then processed outside the vacuum vessel and fed back into the plasma. (see drawings of slide 8 or 9)

b) Each D-T fusion reaction produces only one neutron. In order to achieve a self-sustaining fusion reaction, every neutron must be captured and transmuted into tritium. In reality losses are unavoidable.

c) A neutron multiplier can be placed before the neutron interact with lithium. For example, a neutron capture by Be or Pb resulted in the release of 2 neutrons.

d) The average multiplication of neutrons in a fusion reactor can be represented by the tritium breeding ratio (TBR). Any blanket technologies strife to go for high TBR value, but there is a minimum value that is required to:

- compensate for decay losses (5.47% per year)
- maintain a tritium reserve for operations
- supply tritium to start new reactors

this minimum value should not exceed the maximum achievable TBR of blanket technologies.

Exercise 4.

Outline the main positive and negative aspects on the safety of a deuterium-tritium fusion reactor,

a) What specific challenges are related to the safety of operating a tritium-fuelled fusion power plant?

b) What can be done to overcome those challenges?

Solution 4.

a)

- Tritium extraction: Separating the produced tritium from the breeding blankets and recovering it from wall components and vacuum systems.
- Material activation and embrittlement: Making the reactor vessel components resistant to high fluxes of 14 MeV neutrons.
- Radiological safety: Preventing significant human contact with tritium and tritium-contaminated materials, as well as with materials activated by 14 MeV neutrons.
- Remote handling: Performing plasma operations and maintenance without direct human contact with the reactor vessel or fuel supply.
- Plant decommissioning: Activated vessel components remain hazardously radioactive on a time scale of roughly 100 years.

b)

- Tritium extraction: Electrolysis, catalysis, membrane diffusion, dedicated plasma discharges for wall conditioning
- Material activation: Development of reduced-activation materials
- Radiological safety: Following strict safety protocols
- Remote handling: Robotics and automation
- Plant decommissioning: Similar to fission plants, but shorter time requirements