Fusion Technology question #5: Tritium burn and retention
As usual, show all work!

I. Determine the T burnup fraction in ITER

Take ITER case of P_{Fus}=500 MW and a core plasma volume ~ 630 m^3 . Core plasma temeperature is 10 keV.
The DT fusion reaction rate can be approximated by $<\sigma v>_{DT,fusion} \sim 1\times10^{-22}\ m^3/s \times (T[keV]/10)^2$ between 5keV and 25 keV.
The triton (n_T) and deuterium ion (n_D) densities are equal.

a) Calculate the total number of tritons in the core assuming a flat n_T profile, constant over the entire plasma volume.

b) Assuming the plasma is everywhere locally neutral (sum of charges from electrons, D^+, T^+, and He^{++}=0) write down an equation for the fusion power, P_{fus}, as a function of Z_{He} and the helium fraction in the core plasma, $f_{He,core} = n_{He}/n_e$.

c) Determine the value of $f_{He,core}$ that corresponds to a 20% drop in P_{fus} from the case of $f_{He,core}$ = 0; Of course that is not a real case as there must be He in the plasma. But that is the assumption for this simple calculation.

d) Determine the Tritium burnup fraction, f_{burn}; the fraction of T injected into the vessel, $\Phi_{T,puff}$, that is 'burned' through fusion. The neutral T could be injected as a gas (puffed) or injected as pellets of frozen DT. In steady state what is injected, $\Phi_{T,puff}$, must be ~ equal to the T removed from the tokamak, $\Phi_{T,pump}$, as the burn fraction is small.

$$f_{burn} = \frac{\text{Triton burn rate}}{\text{Triton injection rate}} = \frac{\Phi_{T,burn}}{\Phi_{T,puff}} \sim \frac{\Phi_{T,burn}}{\Phi_{T,pump}} = \frac{\Phi_{He,pump}}{\Phi_{T,pump}}$$

I have utilised that the T burned in the vessel = the He pumped out of the vessel. Similar to the core He concentration, $f_{he,core}$, we define the neutral He concentration in the divertor, $f_{He,div}$, as

$$f_{He,div} \equiv \left(\frac{n_{0,He}}{n_{0,D} + n_{0,T} + n_{0,He}} \right) \sim \frac{n_{0,He}}{2n_{0,T}}$$

The (de)enrichment of He in the divertor compared to the core, $\eta_{He} = f_{He,div}/ f_{He,core}$, is measured to be ~0.2 in some experiments. Use $f_{He,core}$ from 1c. Make sure your equation for f_{burn} includes both $f_{He,core}$ and η_{He}, all of which will be small compared to 1.

II. Explore the level of the incident T^+ flux that can be retained in tiles without exceeding the in-vessel T limit of 640g

Assume the heat flux to tiles, $q_\perp$, in ITER is $10MW/m^2$ and is related to the ion flux as $q_\perp = \Gamma^+ \gamma k T_e$. The total incident heat, and thus, the total incident particle flux, can be determined through using an area of 5 m^2, a sheath transmission factor, γ of 7, and $T_{e,target}$~5 eV. Assume ITER pulses are 400s in length, once per hour, over 6 months of the year.

a) Calculate the total ion flux to the $5m^2$ of tiles in #/second.

b) Given the in-vessel T limit of what can be retained inside the vessel (in tiles), and that the tiles will not be replaced for 5 years, what is the maximum fraction of the T ions incident on the 5 m^2 of tiles that can be retained in the tiles? For this simple calculation assume that there is no ion flux to surfaces outside the $5m^2$ specified.

c) Repeat 2b but for a DEMO (same $10MW/m^2$ limit) where the total amount of divertor area is tripled ($15m^2$) and the fractional runtime (hours run per year)/total hours per year) =75% (fusion burn year=0.75). Discuss ways to attain such retention levels. Also discuss ideas for measuring T retention in vessel.

III. Exhaust gas processing – T must be removed and purified from the exhaust gas

a) Given a T burnup fraction of 1% calculate the rate at which the exhausted T must be separated and prepared to be re-injected in ITER during the hours of operation. Note that the allowable onsite is 2-3 kg with 640g allowed inside the vessel.

b) Make the same calculation for DEMO with 5x the fusion reaction rate as ITER. Comment on the implications for DEMO.