Prof. M. A. Abdou
TA: Tyler Rhodes

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MAE 237D

Fusion Engineering and Design

FINAL EXAM

Take Home Exam

Due: Thursday, March 17, 2016
at 4:00pm
(Submit in 44-114 Eng IV to Emily or Jesse)

Attempt Only Six Problems

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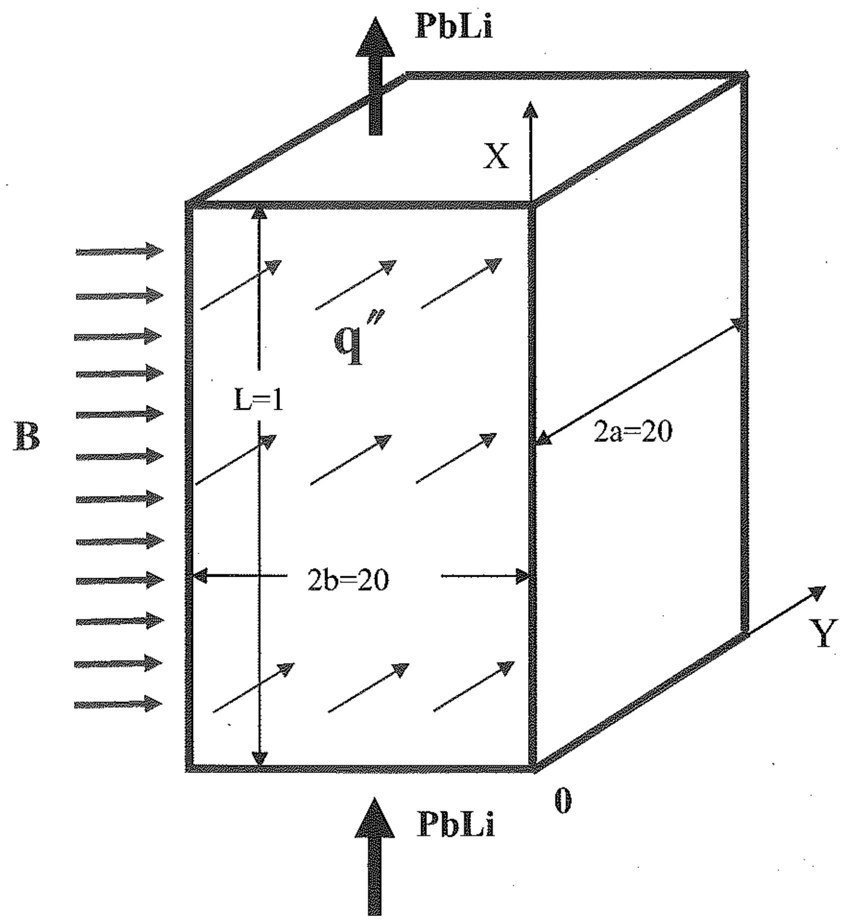
- **Include the details of your solutions**
- **Provide informal citations for any sources used**
- **Make, indicate, and justify any significant assumptions**
- **Please work independently**

Problem 1

In a self-cooled poloidal PbLi blanket, the liquid metal flows through rectangular ducts made of RAFM steel. The wall thickness of the duct is 2 mm. Consider one of the front ducts (facing the plasma), assuming idealized conditions when the duct is fully decoupled electrically from the rest of the blanket and also neglect heat exchange with all other ducts. The flow velocity is 0.5 m/s. The toroidal magnetic field is 5 T. The PbLi flow is exposed to volumetric heating that varies with the radial distance y as $q'''(y) = 30\times10^6 \exp\{-y/a\}$, W/m^3. The surface heat flux is 0.5 MW/m^2. The inlet temperature in the PbLi is 400°C. The internal duct cross-sectional dimensions $2a$ and $2b$ and the length L are shown in the figure.

a) Calculate basic dimensionless parameters: the Hartmann number *Ha*, Reynolds number *Re*, magnetic Reynolds number Re_m, interaction parameter *N*, and the wall conductance ratio *c*.
b) Estimate the MHD pressure drop without and with electrical insulation (assuming ideal electrical insulation).
c) What can you say about the shape of the velocity profile in the two cases: (1) if the duct is perfectly insulated; and (2) if there is no any electrical insulation?
d) What flow regime (laminar or turbulent) will likely occur?
e) Estimate temperature increase in PbLi: Tout-Tin.



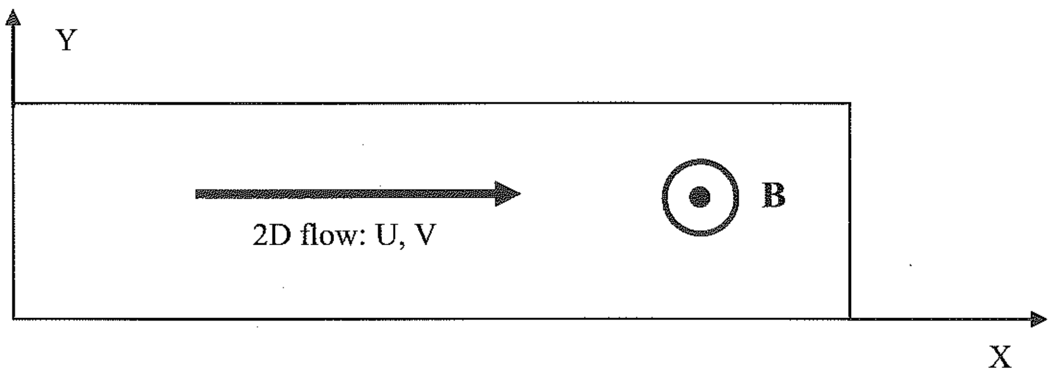
Physical properties

Fe: σ=1.4×10^6 1/Ohm-m, k=33 W/m-K, ρ=7800 kg/m3, C_p=750 J/kg-K

PbLi: σ=0.7×10^6 1/Ohm-m, k=15 W/m-K, ρ=9300 kg/m^3, C_p=190 J/kg-K, μ=0.001 Pa-s

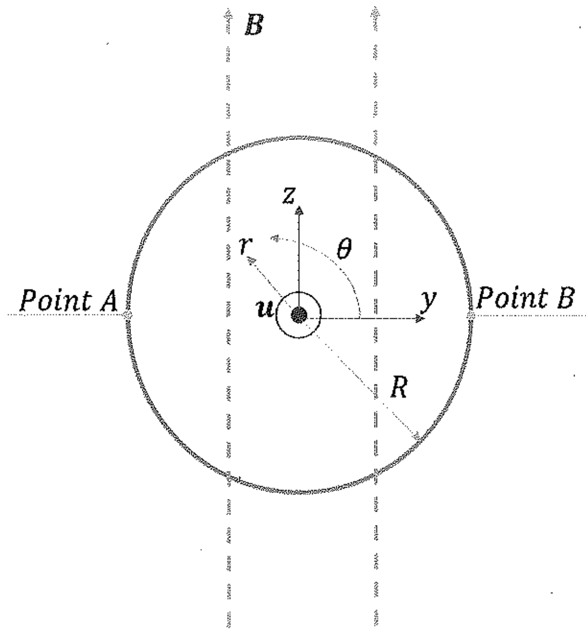
Problem 2

Derive the vorticity equation ($\omega = \frac{\partial U}{\partial y} - \frac{\partial V}{\partial x}$) for a 2D MHD flow (in the x-y plane) of electrically conducting fluid in a constant spanwise magnetic field (the field is in z direction). Based on this equation conclude what kind of MHD effect will be experienced by the flow.



Problem 3

Consider a fully developed MHD flow in a non-conducting circular pipe with radius R in the presence of a uniform magnetic field in the z-direction ($\boldsymbol{B} = B\widehat{e_z}$) as shown in the figure.



For such a configuration evaluate the following:

a) The distribution of electric potential along the wall (r = R) of the pipe for a given axisymmetric velocity profile $\boldsymbol{u}(r) = 2u_{avg}\left(1 - \frac{r^2}{R^2}\right)\widehat{e_x}$ (here u_{avg} is the average fluid velocity) by solving 2D Poisson equation for electric potential in the y-z plane with the assumption that the velocity profile is not affected by the magnetic field. *[HINT: Use the method of separation of variables.]*

b) Potential difference between points A and B for magnetic field strength B of 1 Tesla, average velocity u_{avg} of 10 cm/sec and pipe radius R of 10 cm.

Problem 4

a) Draw a schematic of a vertical cross-section of a tokamak reactor showing all major reactor components.

b) Describe concisely the functions of all components in (a) above.

c) What is the main difference between a tokamak and other toroidal confinement plasma devices?

d) Draw a unit cell of a DCLL blanket illustrating the primary geometric regions and materials.

e) Compare the features, advantages and disadvantages, of DCLL blanket to separately cooled PbLi blanket.

f) Discuss how tritium is extracted from ceramic breeder blankets.

Problem 5

A tokamak reactor with superconducting TF coils has a major radius of 6.8m, an aspect ratio of 3, and a neutron wall load of 3.6 MW/m^2. It has a breeding blanket that attenuates the neutrons by two orders of magnitude followed by 90 cm of 85% Pb+15% B_4C.

a) Calculate the reactor fusion power.

b) Calculate the total heat load into the cryogenic system.

c) Calculate the total power required to remove the nuclear heating deposited in the magnet.

d) Calculate the radiation-induced resistivity in the copper stabilizer at the point of maximum magnetic field after 4 years of continuous reactor operation.

e) If the tritium breading ratio is 1.15, calculate the rate of tritium production in the blanket in kg/s.

Problem 6

a) State and explain cryogenic stabilization criterion for superconducting magnet.

b) Discuss concisely radiation effects on components of superconducting magnets.

c) Compare the functions of bulk shielding, penetration shielding, and biological shielding in a tokamak fusion power plant.

d) What is the most promising structural material for a fusion DEMO? Why?

Problem 7

a) Calculate Q values for Li^6 (n, t) and Li^7 (n, n't), and specify if they are exothermic or endothermic.

b) If a 1 MeV neutron undergoes elastic scattering at 45 degrees with a Li^6 target in the blanket what is the heat deposited in the material per interaction?

c) An (n,α) reaction in a particular nuclide has a Q-value of -5 MeV calculate the neutron kerma factor for 14 MeV neutrons.

d) A particular shield composition has a total energy attenuation coefficient of 0.138 cm^{-1}, what is the shield thickness required to achieve energy attenuation of four orders of magnitude?

e) Write down the Neutron Transport Equation and describe the physical meaning of each term. Which term is the one that requires a more difficult mathematical treatment?

f) Neutronics calculations for a fusion blanket show the following reaction rates per fusion neutron:

REACTION	REACTION RATE Per fusion neutron	|Q| - VALUE MeV
V(n,2n)	0.1	− 13
V(n,γ)	0.05	+ 8
^{6}Li(n,α)	0.80	+ 4.8
^{7}Li(n,γ)	0.02	+ 5
^{7}Li(n,n',α)	0.4	− 2.4

f1) Calculate the tritium breeding ratio.

f2) Calculate the energy multiplication factor

f3) If a tokamak reactor using the above blanket produces 3000 MW of fusion power and has a thermal conversion efficiency of 35%, calculate the reactor electric power output.

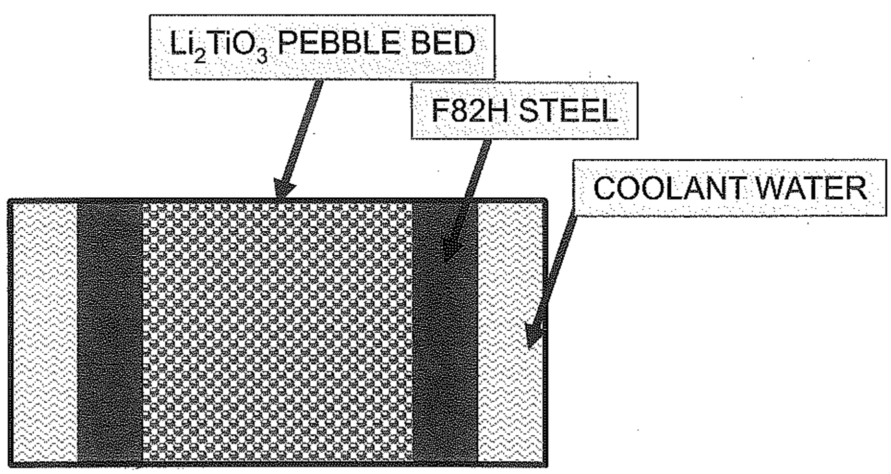
Problem 8

Consider a 1D, pebble bed-type blanket configuration with a 2-cm wide (along the tokamak's radial direction) breeder volume cooled on both sides by water at a bulk temperature of $T_f = 300$ °C. Water is flowing at 5 m/s through an equivalent hydraulic coolant channel of 1 cm with a structural wall thickness of 3 mm. (See the sketch below)

a) Calculate the temperature distribution across the pebble breeder element, structure, and water, considering the following:
   - Single size pebble bed of lithium Li_2TiO_3 pebbles of 1 mm diameter.
   - Constant volumetric heat generation rate in the breeder region of 8 MW/m^3
   - A temperature jump of 25 °C exists at the interface of pebble bed and steel
   - Use thermal properties of stainless steel for F82H

b) Calculate the purge gas pressure drop across a 1 meter tall pebble bed as a function of superficial purge gas velocity of 1, 5, and 10 cm/s for a single size bed of 1 mm pebble. Assume an average purge gas temperature of 600 °C and random packing of spheres.

c) How much tritium will permeate to the coolant from the pebble bed region through the F82H wall, if the superficial purge gas velocity is 1, 5, and 10 cm/s?
   - Assume diffusion limited control.
   - Average tritium generation rate in the breeder region= 1.21e-7 g/s.
   - Use bed average temperature for tritium partial pressure estimation.



Probl 1]

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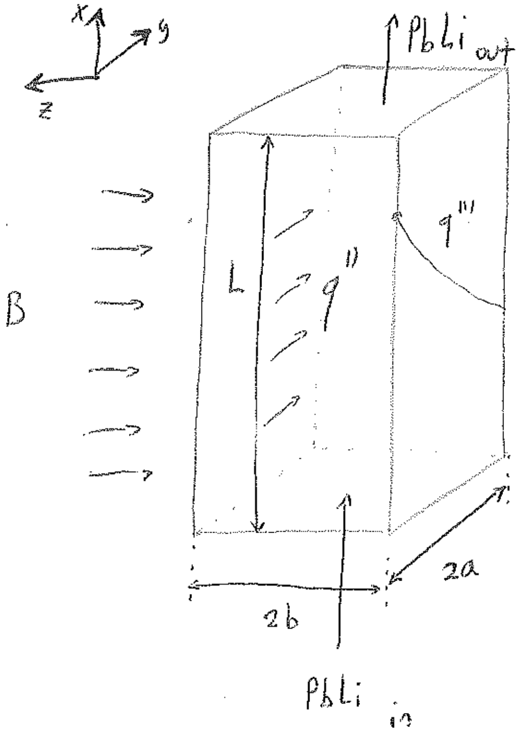


$t_w = 2\ mm = 0.002\ m$

$V = 0.5\ m/s$

$B = 5\ T$

$q'''(y) = 30 \times 10^6 \exp\{-y/a\} \quad W/m^3$

$q'' = 0.5\ MW/m^2 = 0.5 \times 10^6\ W/m^2$

$T_{in} = 400\ °C$

$2a \times 2b \qquad 2a = 2b = 20\ cm = 0.2\ m$

$L = 1\ m$

$\sigma_{Fe} = 1.4 \cdot 10^6\ \Omega^{-1} m^{-1} \qquad k_{Fe} = 33\ \frac{W}{m\,k}$

$\rho_{Fe} = 7800\ kg/m^3 \qquad c_{p_{Fe}} = 750\ \frac{J}{kg\,k}$

$\sigma_{PbLi} = 0.7 \cdot 10^6\ \Omega^{-1} m^{-1}$

$k_{PbLi} = 15\ W/m\text{-}k$

$\rho_{PbLi} = 9300\ kg/m^3$

$c_{P_{PbLi}} = 190\ J/kg\text{-}k$

$\mu_{PbLi} = 0.001\ Pa\text{-}s$

a) $$Ha = B a \sqrt{\frac{\sigma_{PbLi}}{\rho_{PbLi}\,\nu_{PbLi}}} = B a \sqrt{\frac{\sigma_{PbLi}}{\mu_{PbLi}}} =$$

$$= 5 \times 0.1 \times \sqrt{\frac{0.7 \times 10^6}{0.001}} = 1.323 \times 10^4$$

$$Re = \frac{V \times a}{\nu} = \frac{V a \rho}{\mu} = \frac{0.5 \times 0.1 \times 9300}{0.001} = 4.65 \times 10^5$$

$$Re_m = \mu_0 \sigma_{PbLi} a V = 4\pi \times 10^{-7} \times 0.7 \times 10^6 \times 0.1 \times 0.5 = 0.044 = 4.4 \times 10^{-2}$$

$$N = \frac{Ha^2}{Re} = \frac{(1.323 \times 10^4)^2}{4.65 \times 10^5} = 3.76 \times 10^2$$

$$C_w = \frac{\tau_w \sigma_w}{a \sigma_{PbLi}} = \frac{\tau_w \sigma_{Fe}}{a \sigma_{LiPb}} = \frac{0.002 \times 1.4 \times 10^6}{0.1 \times 0.7 \times 10^6} = 0.04 = 4 \times 10^{-2}$$

b) $$\frac{Re}{Ha} = \frac{4.65 \times 10^5}{1.323 \times 10^4} = 35.15 < Re_{crit} \Rightarrow \text{Laminar}$$

$$\Delta p = \lambda \frac{L}{2a} \frac{\rho v^2}{2} \qquad \tanh(Ha) = 1$$

$$\lambda = \frac{8}{Re} \frac{Ha^2}{C_w + 1} \frac{C_w Ha + \tanh Ha}{Ha - \tanh Ha} = \frac{8}{4.65 \times 10^5} \frac{(1.323 \times 10^4)^2}{0.04 + 1} \cdot \frac{0.04 \times 1.323 \cdot 10^4 + \tanh(1.323 \cdot 10^4)}{1.323 \cdot 10^4 - \tanh(1.323 \cdot 10^4)}$$

$$= 116.05$$

$$\Delta p_{cond} = 116.05 \cdot \frac{1}{0.2} \times \frac{9300 \times 0.5^2}{2} = 674.526 \text{ KPa}$$

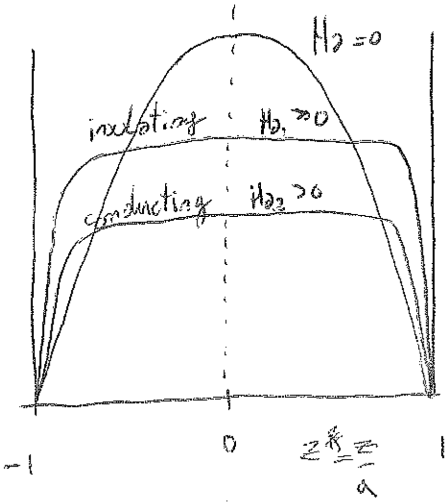
when perfectly insulating $C_w = 0$

$$\lambda = \frac{8}{4.65 \times 10^5} \frac{(1.323 \cdot 10^4)^2}{1} \frac{1}{1.323 \times 10^4 - 1} \quad 0.228$$

$$\Delta p_{ins} = 0.228 \frac{1}{0.2} \frac{9300 \times 0.5^2}{2} = 1.325 \text{ KPa}$$

$$\Delta p_{ins} = 1.96 \cdot 10^{-3} \Delta p_{cond}$$

c)



$Ha_1 = Ha_2$

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Current induced by $\vec{u}\times\vec{B}$ close through the walls and in the fluid viscous layer. these currents are higher than the insulating condition (for which currents close in the fluid without penetrating the walls).

As a consequence, the pressure drop and the Lorentz force $\vec{J}\times\vec{B}$ are higher. In particular, in the core region, the Lorentz force acts in the opposite to the mean flow thereby, retarding it. In the Hartmann layer velocity are lower and in both cases $\vec{J}\times\vec{B}$ drives the fluid against viscous braking. (Compared to the case $Ha=0$ we have higher velocities in the layer and lower in the core; in particular $v_{\substack{center\\Line\\z^*=0}}$, insulating $>$ $v_{\substack{center\\Line\\z^*=0}}$; conducting.)

d) The transition to turbulence is governed by the Ratio $R=\frac{Re}{Ha}$ Because of the very high Ha number obtained the ratio is very small $R = 35.15 < R_{crit}$ therefore the flow is laminal

e) energy balance

$$\dot{m}_{PbLi}\, c_{p_{PbLi}} \left(T_o - T_i \right) = q'' \cdot A + \int_{vol} q''' \, dVol \qquad [W]$$

$$A = L \times 2b = 1 \times 0.2 = 0.2 \ m^2$$

$$\dot{m}_{PbLi} = \rho_{PbLi} \times V \times A_c \qquad \Rightarrow \dot{m}_{PbLi} = 9300 \times 0.5 \times 0.04 = 186 \ \frac{kg}{s}$$

$$A_c = 2a \times 2b = 0.2 \times 0.2 = 0.04 \ m^2$$

$$\int_{vol} q''' \, dVol = 30 \times 10^6 \int_0^{2b} dz \int_0^{2a} dy \int_0^{L} dx \ \exp\left\{ -y/a \right\} = 30 \times 10^6 \times 2b \times L \times \left[- \frac{\exp\left(-y/a\right)}{\frac{1}{a}} \right]_0^{2a} =$$

$$= 30 \times 10^6 \times 0.2 \times 1 \times 0.1 \left[-\left(\exp(-2) - \exp(0) \right) \right] = 518.799 \times 10^3 \ W = Q$$

$$T_o - T_i = \Delta T = \frac{q'' A + Q}{\dot{m}_{PbLi}\, c_{p_{PbLi}}} = \frac{0.5 \times 10^6 \times 0.2 + 518.799 \times 10^3 \ [W]}{186 \times 190 \ \left[\frac{W}{K} \right]} =$$

$$= 17.5 \ [K]$$

This small ΔT is due to the relatively high velocity. If the velocity is reduced to 0.1 m/s whe obtain a $\Delta T \sim 87.5$ [K].

Problem 4]

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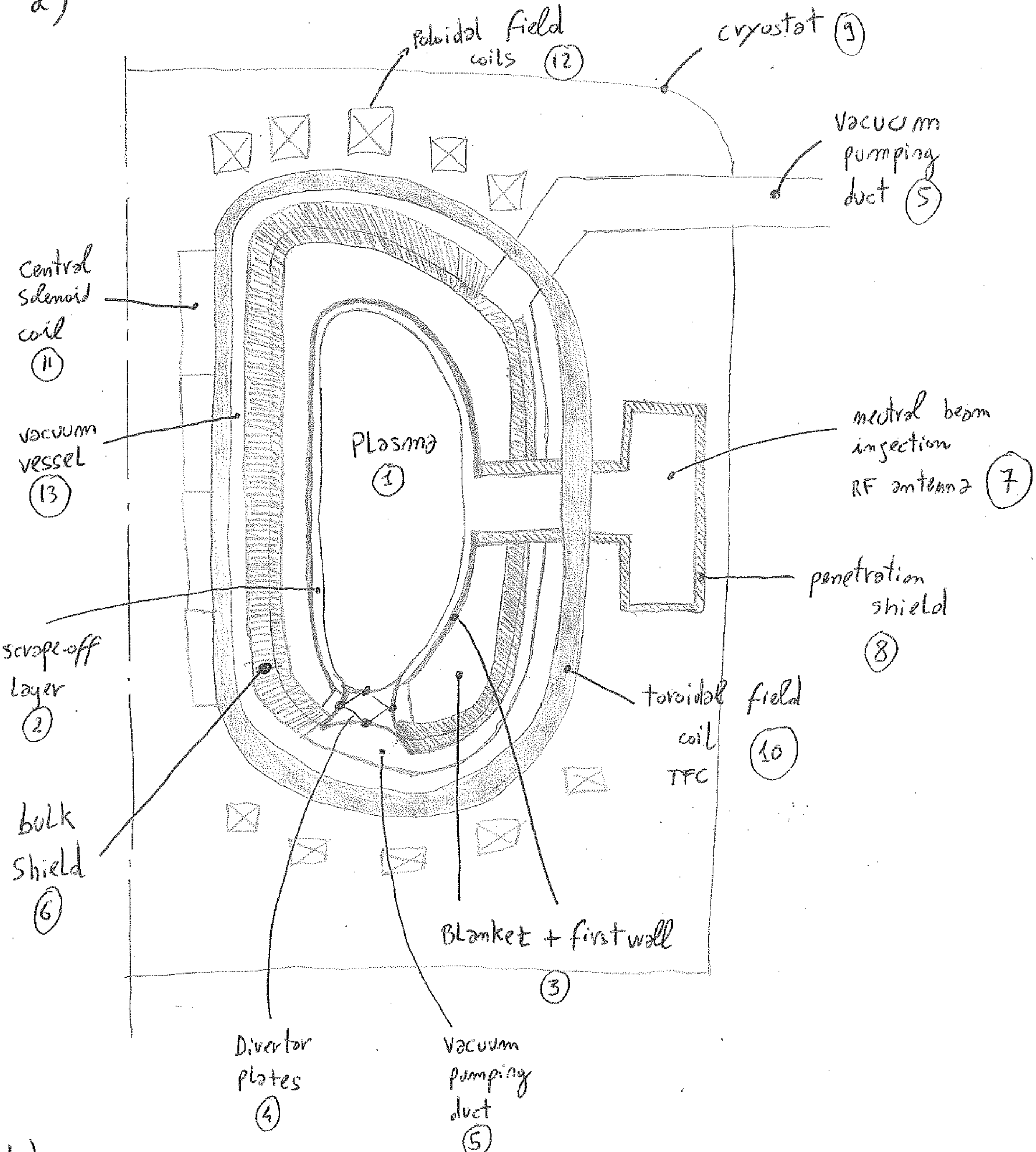
a)



b) (1) Plasma: In the plasma nuclear fusion reactions ($D + T \rightarrow \alpha + n$ for instance) occur.

(2) Scrape-off layer SOL: It is the region characterized by open field lines, i.e. the region outside the separatrix (divertor configuration). It absorbs most of plasma exhaust particles and heat and transports them to the divertor

Plates where they are pumped out.

③ First wall / Blanket: They are responsible for converting neutrons kinetic energy and secondary gamma rays into heat (power conversion). Heat has to be extracted at high temperature. the first wall absorbs plasma radiation.

Blankets are used for tritium breeding. Lithium in solid or liquid form absorbs a neutron and releases tritium and a α particle (if Li^6) or tritium, α-particle and a lower energy neutron n' (if Li^7). Tritium is then extracted.

At the same time, blankets provide a physical boundary surrounding the plasma inside the vacuum vessel and give access to plasma for fueling or plasma heating. They are the first shield of radiation.

④ Divertor plates: plasma exhaust particles are collected by divertor plates and pumped out by divertor pumps. the Divertor allows waste managment "online" while the reactor is operating.

⑤ Vacuum pumping duct: Duct used to evacuate the torus and provide divertor pumping. It is connected to a high vacuum pumping system.

⑥ Bulk shield: It is fundamental to protect equipment and personnel.
Its function is leaking neutrons and gammas attenuation and absorption.

⑦ Neutral Beam Injection / RF antenna: Devices responsible for plasma heating. They inject neutral particles or electromagnetic waves into the plasma throughout penetrations.

⑧ Penetration shield: It shields penetrations from high energy neutrons coming from the plasma.

⑨ Cryostat: It provides high vacuum and super-cool environment for super conducting magnets.

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(10) Toroidal field coils: They generate a strong toroidal magnetic field for plasma confinment. Maximum toroidal field in ITER is 11.8 T.

(11) Central Solenoid: It is considered the primary circuit of a transformer (plasma is the secondary circuit). The central Solenoid discharge induces a toroidal current in the plasma which generates a poloidal magnetic field. This poloidal field is fundamental to confine the plasma since the toroidal field only is not sufficient. Due to velocity drifts, a vertical electric field arises and the consequent $\vec{E} \times \vec{B}$ drives the plasma away. The poloidal field mitigates these effects.

(12) Poloidal field coils: they control plasma plasma instabilities and shape (typical "D" shape)

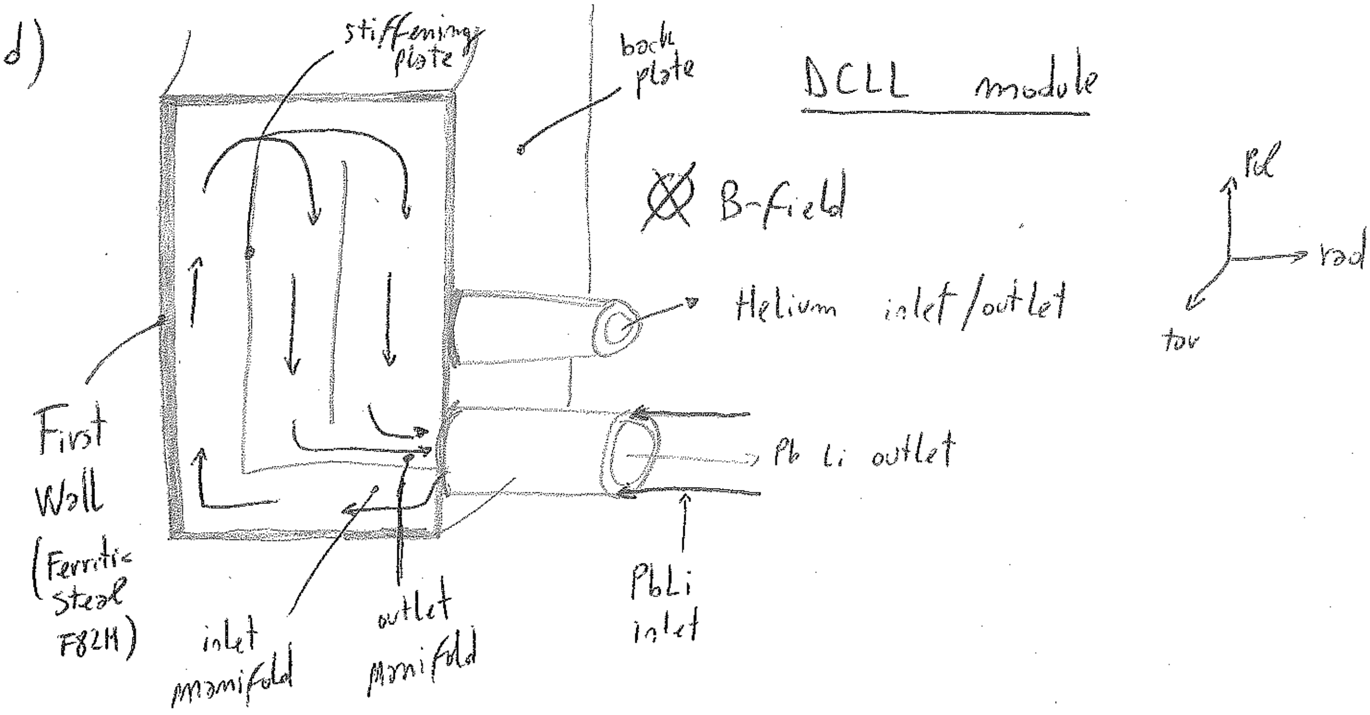
(13) Vacuum vessel: Hermetically-sealed steel container that contains shield, blankt/FW, SOL and plasma, and acts as a safety barrier. It contains all that is radioactive and, therefore, it has to be very reliable. To avoid failures the amount of helium generated in the lifetime in vacuum vessel has to be < 1 appm.

c) The tokamak is characterized by a magnetic field confing the plasma produced by three sets of magnets (Toroidal field coils, central solenoid coils, poloidal field coils). In a tokamak we have a strong toroidal current which is needed to induce the poloidal field. The system of magnets is relatively easy to build.

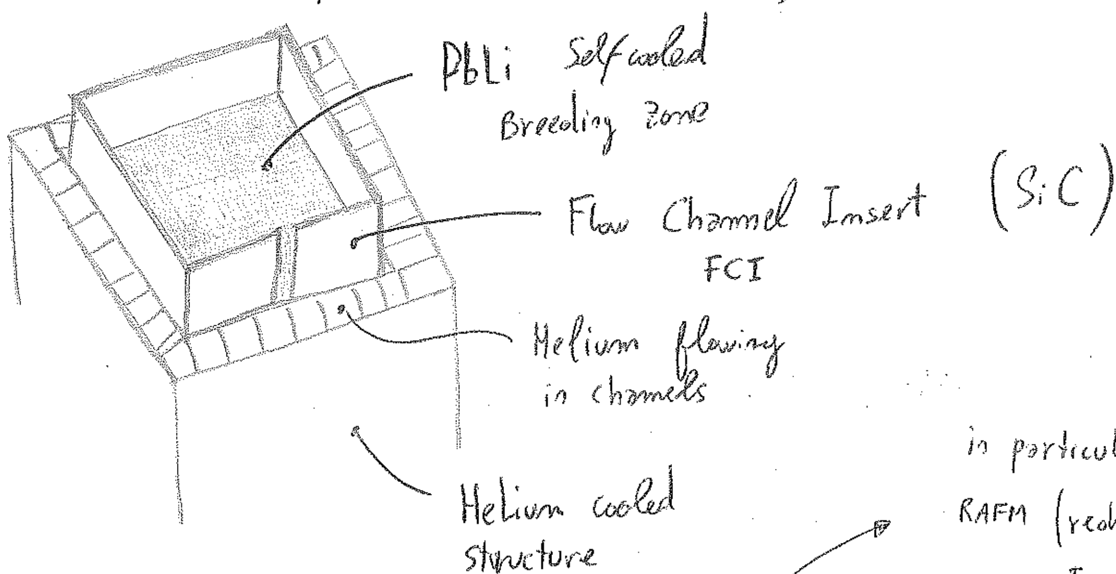
Another toroidal device is the so-called Stellarator. In this device field lines are manipulated with external currents. A very complex system of magnets is required. In particular, magnets shape is very hard to be built. They have no azimuthally symmetric magnetic field topology. They are interesting from a stability point of view sicnce the absence of a strong toroidal current makes them more stable then tokamaks. On the other hand, the design is very complex and they are challenging to build.

d)

DCLL module



Top view in toroidal - poloidal plane (one channel) UNIT CELL



in particular they are RAFM (reduced Activation Ferritic/Martensitic)

First wall and structure is Ferritic Steel (F82H for example) cooled by helium at ~ 8 MPa. The breeding zone Pb83-Li17 is self-cooled; velocity is kept low (~ 10 cm/s). FCI separates the structure and Breeding zone; it is made by SiCf/SiC composite which works as thermal/electrical insulator.

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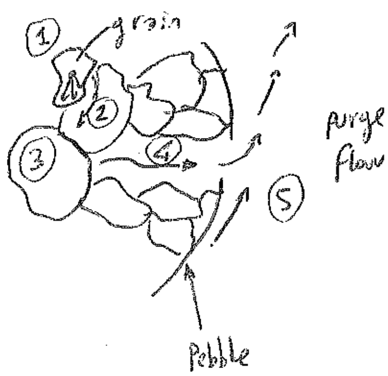
e) In separately-cooled PbLi blanket all energy is removed by separate Helium stream. PbLi circulates as breeder to produce tritium. They are designed in order to minimize the mhd issues. However, the low velocity of PbLi (0.5–1.5 mm/s) leads to very high tritium partial pressure $P_t \propto 1/v$ and, therefore, to tritium permeation. This is a serious problem in terms of safety (because of radioactivity of tritium). Also, the outlet temperature of PbLi is limited to 500°C or 550°C with RAFM steel structure or Ferritic steel respectively. As a consequence, they are not very efficient from a thermal point of view. Other problems could be the MHD pressure drop in the inlet manifold and the effect of MHD buoyancy-driven flows (since forced convection is very low because of the very low velocity of PbLi). These problems are very challenging to solve if not unsolvable.

The DCLL concept solves most of these problems. The main difference, compared to the separately-cooled design, is that PbLi is itself used as a coolant (not only as a breeder). For this reason, it flows at higher velocity (~10 cm/s) reducing at the same time tritium permeation. In order to have a high thermal efficiency, PbLi reaches higher temperatures (~750°C). Problems in compatibility with Ferritic Steel structure are avoided using a second coolant (Helium at 8 MPa) which keeps the structure at a temperature lower than 550°C (limit for Ferritic Steel). An important component is the Flow channel inserts FCI (SiCf/SiC composite) which has two functions:

- it provides thermal insulation decupling the liquid metal flow from the structure
- it provides electrical insulation to reduce the MHD drop in the flowing breeding zone.

In conclusion, the DCLL offers better thermal efficiency and reduces tritium permeation and related safety problems. Nevertheless, mhd pressure drop in manifolds is still high and has to be reduced.

f) In solid breeders tritium is removed with a purge gas (usually Helium at 1 atm) which flows through the porosity of packed beds of lithium ceramics. Tritium release is a function of grain size, microstructure and open/closed porosity. Tritium recover is obtained in five steps:



1] intergranular diffusion (bulk diffusion)

2] Grain boundary diffusion

3] Surface Adsorption/Desorption

4] Pore diffusion

5] Purge flow Convection

In particular bulk diffusion is a significant contributor to tritium inventory T.

$$T = \frac{1}{15} \dot{T} \frac{r_p^2}{D}$$

where r_p is the radius of spherical particles and $D = 0.16\, r_p^2/\tau$ the diffusivity (τ residence time).

$\dot{T}$ is the tritium generation rate.

Probl 5]

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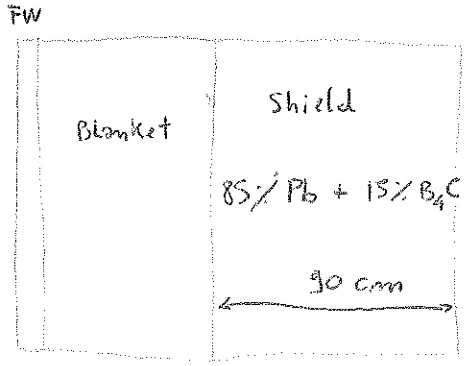
$R = 6.8$ m

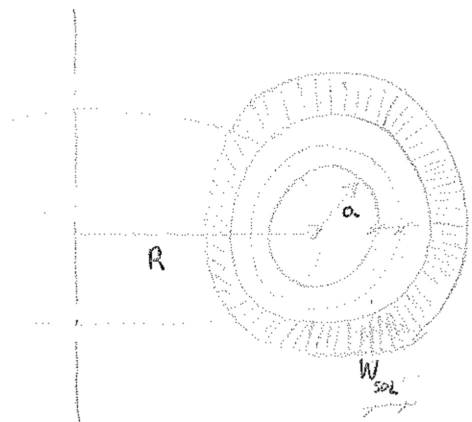
$\frac{R}{a} = 3$

wall load $= 3.6$ MW/m^2 $= P_{mw}$



a)

$$A_{FW} = 2\pi r \times 2\pi R = 4\pi^2 r R$$



$r = a + W_{sol}$

I assume $W_{sol} = 0.01\,m$

$$a = R/3 = \frac{6.8}{3} = 2.27\,m$$

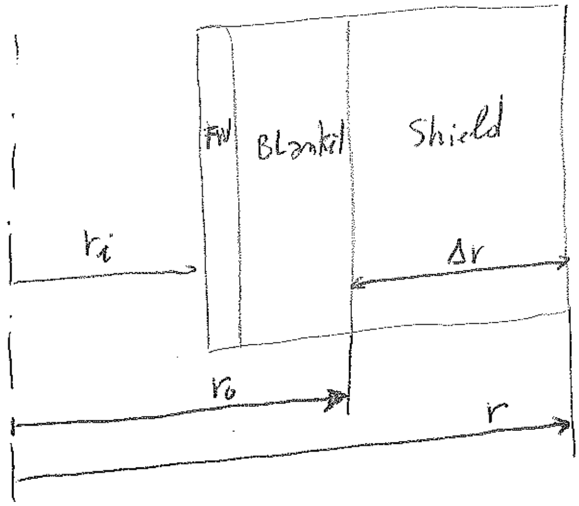
$$r = a + W_{sol} = 2.28\,m$$

$$A_{FW} = 4\pi^2 r R = 4\pi^2 \times 6.8 \times 2.28 = 612.07\ m^2$$

$$P_n = P_{mw} \times A_{FW} = 3.6 \times 612.07 = 2.203 \times 10^3\ MW$$

$$P_f = P_n \times \frac{17.58}{14.06} = 2,755.11\ MW$$

b) blanket attenuates 2 orders of magnitude, then there is the shield



energy leakage

$$\frac{L_E(r)}{L_E(r_0)} = e^{-\mu_t (r - r_0)} = e^{-\mu_t \Delta r}$$

$\Delta r = 90$ cm

for $85\%\ Pb + 15\%\ B_4C$ $\quad \mu_t = 0.0976\ cm^{-1}$ (handout n. 13)

we need to find $L_E(r_0)$ in order to get $L_E(r)$ and therefore the heat loading. To do so, we need $L_E(r_i)$.

L_E is defined as $\quad L_E(r) = Area \times \sum_g E_{mg} J_{mg}$

we assume monoenergetic neutrons at 14.06 MeV $= E_0 \Rightarrow L_E = Area \times J E_0$

by definition the neutron wall load is $P_{nw} = J E_0$ where J is the virgin current $\left(\frac{\text{neutrons with } E_0}{s - Area} \text{ i.e. } \frac{\text{Source (14 MeV neutrons/s)}}{\text{Area (First wall)}} \right)$

therefore

$$L_E(r_i) = A_{FW} \times J E_0 = A_{FW} \cdot P_{nw} = P_n$$

$$\frac{L_E(r_0)}{L_E(r_i)} = 10^{-2} \Rightarrow L_E(r_0) = L_E(r_i) \cdot 10^{-2} = 2.203 \times 10^3 \cdot 10^{-2} = 22.03 \text{ MW}$$

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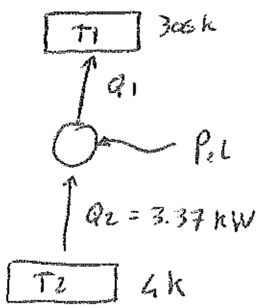
therefore, after the shield

$$L_E(r) = L_E(r_0)\, e^{-\mu_t \Delta r} = 22.03 \times \exp\left[-0.0976 \times 90\right] = 3.37 \times 10^{-3}\,\text{MW} = 3.37\,\text{kW}$$

3.37 kW is deposited in the cryogenic system

c) Assuming ideal thermodynamic cryogenic system (reversed Carnot cycle) and magnets temperature of 4 K. The heat is rejected at room temperature 300 K



$$\eta = \frac{Q_2}{P_{el}} \qquad P_{el} = \frac{Q_2}{\eta}$$

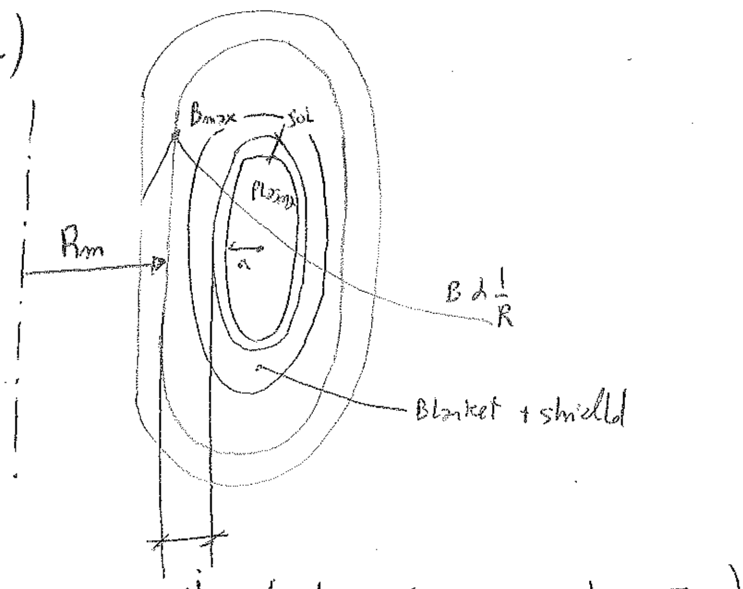
$$\eta = \frac{T_2}{T_1 - T_2} = \frac{4}{300-4} = 0.0135$$

$$P_{el} = \frac{3.37}{0.0135} = 249.63\ \text{kW}$$

We note that ~ 250 kW are needed to remove 1 kW of heat at 4 K.

To reduce the P_{el} other shield materials might be considered. For instance $70\%\,SS + 30\%\,B_4C$ offers $\mu_t = 0.1445$ and would considerably reduce the energy leaking for a fixed shield thickness.

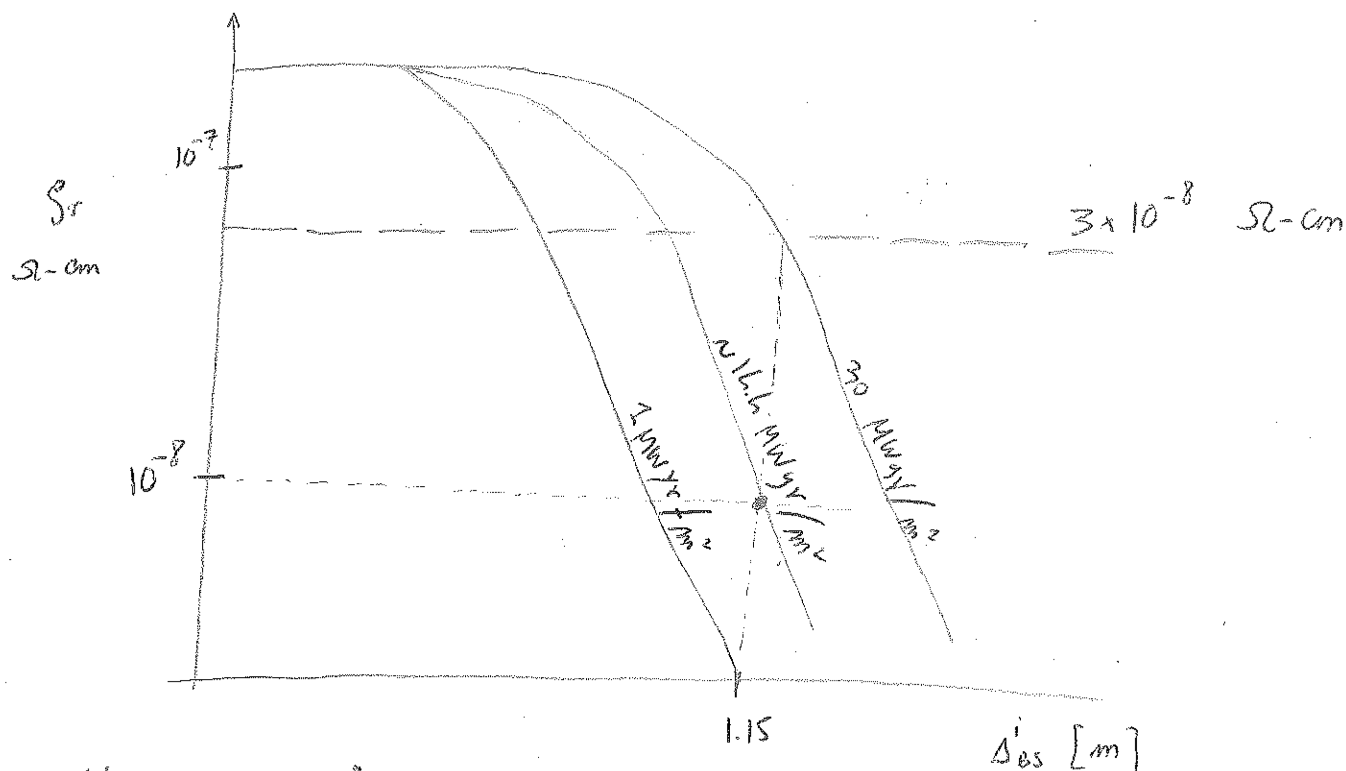
d)



Δ'_{BS} (distance from FW to TFC)

Assuming a total Δ'_{BS} of 1.15m including Blanket and shield and using the following graph of handout (13) for a integrated neutron wall load of

$$I_{nw} = P_{nw} \times t = 3.6 \times 4 = 14.4 \quad MW\text{-}yr/m^2$$



we obtain $\rho_r = 10^{-8}$ Ω-cm

ρ_r has also been determined empirically as a function of dpa

$$\rho_r = 3 \times 10^{-7} \left(1 - e^{-563 dpa}\right)$$

e) $TBR = \frac{\dot{T}^{+}}{\dot{T}^{-}} = \frac{\dot{T}^{+}}{n_{source}}$ for a DT plasma

$TBR = 1.15 \Rightarrow 1.15\ T_{produced}$ each n burnt

$J = \frac{S}{A_w}$ $\quad S = J A_w = \frac{P_{nw}}{E_0} \cdot A_{FW} = \frac{P_n}{E_0} = P_f \cdot \frac{E_0}{17.58} \frac{1}{E_0} = \frac{P_f}{17.58}$ here P_f is in $\frac{MeV}{s}$

we can convert to $W = \frac{J}{s}$

$1\,MeV = 1.602 \times 10^{-19}\ MJ$

$$S = \frac{2{,}755.11\ MW}{17.58\ MeV \times 1.602 \times 10^{-19} \frac{MJ}{MeV}} = 9.78 \times 10^{20}\ \frac{n}{s}$$

total tritium production $= 1.15 \frac{T}{n} \times 9.78 \times 10^{20} \frac{n}{s} = 1.125 \times 10^{21} \frac{T}{s}$

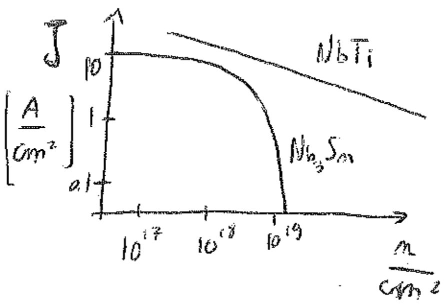
kaeri, nuclear data center

T : 3.01605 u

$m_T = 3.01605\ u \times 1.660 \times 10^{-27} \frac{kg}{u}$

Tritium production $= 1.125 \times 10^{21} \frac{T}{s} \times \left(3.01605 \times 1.660 \times 10^{-27}\right) kg = 5.63 \times 10^{-6} \frac{kg_{tritium}}{s}$

Radiation effect to superconducting magnets is a lower current density J_c.
If J_c decreases, the Area of the component must increase in order to keep a high enough current $I = J_c A_c$. An increase in the area is not economical and expensive. In particular, the critical current density is function of the neutron Fluence as shown in the graph



NbTi is better than Nb_3Sn that drastically decays for a fluence of $8 \cdot 10^{18} \frac{n}{cm^2}$.

Radiation damage, such as displacement per atom dpa, creases drastically material resistivity (or resistance). the resistivity is indeed

$$\rho = \rho_0 + \rho_m + \rho_r$$

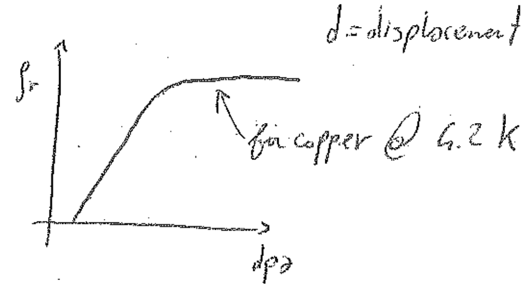
ρ_0: zero magnetic field

ρ_m: magneto resistivity

ρ_r: radiation induced resistivity

$$\rho_r = 3 \times 10^{-7} \left(1 - e^{-563\, d}\right) \ \Omega \cdot cm$$

d = displacement



This has a consequence in terms of the cryogenic stability criterion

$$I^2 \rho \leq q'' P \cdot A$$

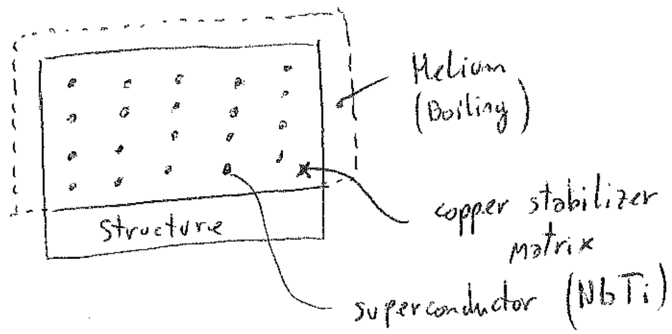
since $q'' = const$, if $\rho \uparrow$ we need to increase A.

Radiation damage can be reduced with annihilation process but this requires a long period of time (4 months) since magnets needs to be heated up and cooled down very slowly in order to avoid thermal stresses. This process can be scheduled in normal maintainance.

Also organic and inorganic insulators properties are damaged by neutron fluence but unfortunately the damage is irreversible. For this reason, the shield design

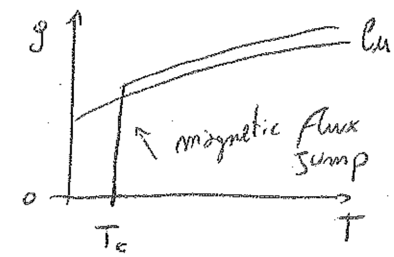
Problem 6] M. Riva

a)
In future fusion reactors like ITER, superconducting magnets will be used in order to minimize the resistivity ρ and avoid heat generation in the magnet which would cause over heating and make impossible the steady state operation. The magnet structure is the following



These magnets stay superconductor if their temperature is lower than 6 K. ($\rho \to 0$ for $T \to 0$ [K])

However, a magnetic flux jump is present between the superconductor and copper. This induces a power generation in the matrix $P = I^2 R$ (I=current, R=resistence). This heat must be removed in a fast enough way to maintain the magnets temperature lower than 6 K. So, it is possible to use a coolant which removes a heat flux q''. To ensure supercondaction we must satisfy



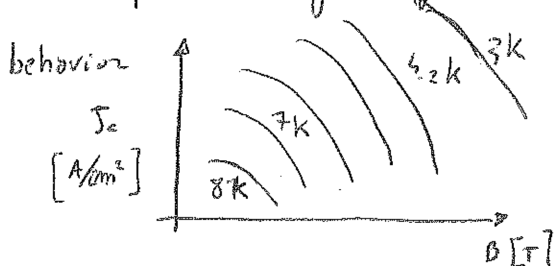
$$I^2 R \le q'' P \cdot l \qquad (P = \text{perimeter},\ l = \text{length})$$

$$I^2 \frac{\rho l}{A} \le q'' P \cdot l \qquad (A = \text{area})$$

$$\boxed{I^2 \rho \le q'' P A}$$

cryogenic stability criterion } when satisfied magnets are superconductor.

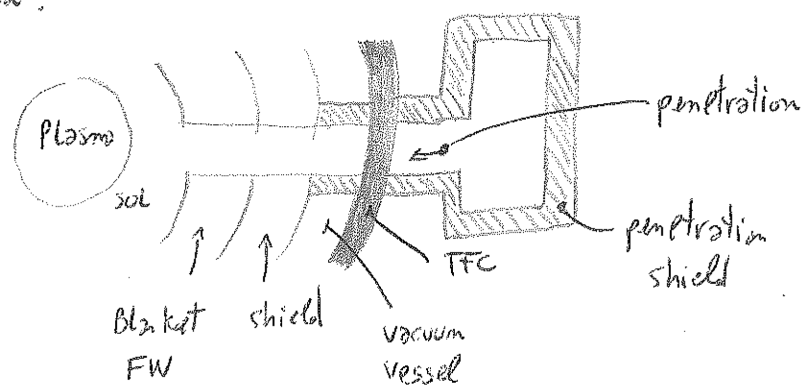
b) Nuclear radiations on superconducting magnet components reduce drastically the superconducting region. For NbTi the critical current has the following behavior



Since low temperatures are necessary, high values of B-field and J_c are needed must ensure the insulator integrity for the whole reactor life. Also inorganic insulators are very brittle.

c) • The bulk shield surrounds the blanket. It is a component of fundamental importance since it is designed to protect the vacuum vessel and superconducting magnets. As explained, superconducting properties of magnets are strongly diminished by radiation, therefore the bulk shield must attenuate and absorb neutrons and gamma rays to prevent radiation damage. After the blanket this is the first shield for equipment and personnel.

• Penetration in the blanket/FW and bulk shield are necessary to access the plasma with neutral beam injection, RF antenna heating / fueling systems. ~~these penetrations~~ Vacuum is induced into these penetration and, therefore, very high energy neutrons can travel in these penetrations and a considerable amount of nuclear radiation can reach the region outside the bulk shield.



A penetration shield is required to protect the region outside the vacuum vessel and TFC.

• Biological shield: It is the last barrier between the reactor and personnel room. It must shield the radiations that have survived and passed the bulk and penetration shield. It usually is a 2 meters thick concrete wall with a metallic liner to prevent tritium permeation. After this shield no radioactivity must be present to protect personnel in central rooms and outside the reactor building.

d) One advantage of the fusion technology is the absence of radioactive products in the fusion process ($D+T \rightarrow \alpha + n$ an α-particles are stable). Neutrons generated in the fusion reactions can, however, activate materials. In order to limit the amount of radioactivity produced we need to carefully choose structural materials. Based on safety, waste management and disposal the candidates are RAFM (Reduced Activation Ferritic/Martensitic) and NFA steels, SiC composites, tungsten alloys on PFC. The main candidate for a DEMO reactor is the ferritic/martensitic steel. This material would assure low activation and resist to the hostile nuclear environment of a fusion reactor (radiations, high temperatures and stresses, chemicals highly reactive). Also, it is compatible with coolant. Commercial alloys are not acceptable in a fusion environment.

Problem 7]

Data from Kaeri, Nuclear data center

$1\ amu = 931.09\ MeV/c^2$

atomic mass unit

M. Riva

a) $Li^6 + n \longrightarrow T + \alpha$

$Li^7 + n \longrightarrow T + \alpha + n'$

Li^6 : 6.01512

Li^7 : 7.01600

α : 4.00260

T : 3.01605

n : 1.00866

$E = mc^2$

$$Q_{Li^6} = \Big[(6.01513 + 1.00866) - (3.01605 + 4.00260)\Big] \times 931 =$$

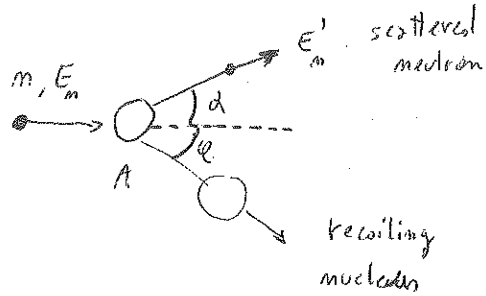
$= 4.76$ MeV exothermic

$$Q_{Li^7} = \Big[(7.01600) - (3.01605 + 4.00260)\Big] \times 931 = -2.47\ MeV$$ endothermic

b) $E_n = 1$ MeV

$\alpha = 45°$

$A_{Li^6} = 6$



$$E_n' = \frac{E_n}{(A+1)^2}\left(\cos\alpha + \sqrt{A^2 - \sin^2\alpha}\right)^2 = \frac{1}{7^2}\left(\cos 45 + \sqrt{6^2 - \sin^2 45}\right)^2 =$$

$= 0.907$ MeV

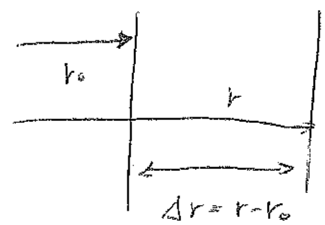
therfore the heat deposited in the material is $1 - 0.907 = 0.093$ MeV

c) (n,d) $\quad Q = -5 \text{ MeV}$, $\quad E_n = 14 \text{ MeV}$

$$E_H = E_n + Q - \cancel{E_{n'}} - \cancel{E_\gamma} + \cancel{E_{di}} = 14 - 5 = 9 \text{ MeV}$$

$$K = \sigma_{n,d} E_H = 9\, \sigma_{n,d} \quad \text{MeV} \times \text{cm}^2$$

d) $\mu_t = 0.138 \text{ cm}^{-1}$



$$\frac{L_{te}(r)}{L_{te}(r_0)} = e^{-\mu_t (r - r_0)} = 10^{-4}$$

$$\ln\left(10^{-4}\right) = -\mu_t \Delta r$$

$$\Delta r = -\frac{\ln\left(10^{-4}\right)}{\mu_t} = 66.74 \quad \text{cm}$$

e) Neutron transport Equation

$$\frac{1}{v}\frac{\partial \varphi}{\partial t} + \hat{\Omega} \cdot \nabla \varphi + \Sigma_t(\vec{r}, E)\, \varphi(\vec{r}, E, \hat{\Omega}, t) = \int_{4\pi} d\hat{\Omega}' \int_0^\infty dE' \, \Sigma_s(E' \to E, \hat{\Omega}' \to \hat{\Omega})\, \varphi(\vec{r}, E, \hat{\Omega}, t) + S(\vec{r}, E, \hat{\Omega}, t)$$

time dependent term

leakage the surfaces (leaking out V through surface S – streaming into V through surface S)

loss due to collision (absorption or loss due to scattering out of dE about E, $\hat{\Omega}$ in $d\hat{\Omega}$)

gain due to scattering into dE about E and direction $\hat{\Omega}$ in $d\hat{\Omega}$. INSCATTERING TERM

neutron source

obtained by the angular current + Gauss' theorem

M. Riva

The inscattering term is the most difficult to treat because we need to consider all contribution from any E', $\hat{\Omega}'$ and integrate over all energies and direction to obtain the neutrons that are at energy E and direction $\hat{\Omega}$ after a scattering event $\Sigma_s(E' \to E, \hat{\Omega}' \to \hat{\Omega})$.

f1) $\frac{\dot{T}_6}{n} = 0.8$, $\frac{\dot{T}_7}{n} = 0.4$

$$TBR = \frac{\dot{T}^+}{\dot{T}^-} = \frac{\dot{T}_6 + \dot{T}_7}{n} = 0.8 + 0.4 = 1.2$$

f2)

$$\varepsilon = \frac{14.06 - 13 \times 0.1 + 8 \times 0.05 + 4.8 \times 0.8 + 5 \times 0.02 - 2.4 \times 0.4}{14.06} = 1.148$$

f3) $P_{fus} = 3000 \text{ MW}_{th}$

$$\eta = \frac{P_{el}}{P_{th}} = 0.35$$

$$P_{th} = P_\alpha + \varepsilon P_n$$

$$P_{el} = \eta P_{th} = \eta \left(P_\alpha + \varepsilon P_n \right)$$

$$P_\alpha = P_{fus} \times \frac{3.52}{17.58}$$

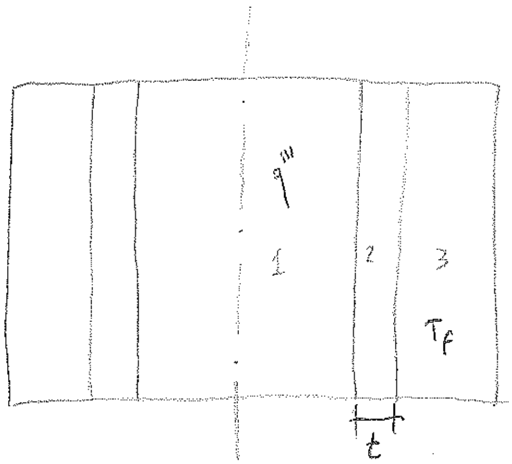
$$P_n = P_{fus} \times \frac{14.06}{17.58}$$

$$P_{el} = 0.35 \times 3000 \times \left(\frac{3.52}{17.58} + 1.148 \frac{14.06}{17.58} \right) =$$

$$= 1{,}174.28 \text{ MW}_{el}$$

Probl 8]

M. Riva



$T_f = 300\,°C$

$V = 5\, m/s$

$D_h = 1\ cm = 0.01\ m$

$t = 3\ mm = 0.003\ m$

pebbles 1 mm diameter

$D_p = 0.001$

$q''' = 8\ MW/m^3 = 8 \times 10^6\ W/m^3$

$\Delta T_{p-s} = 25\,°C$

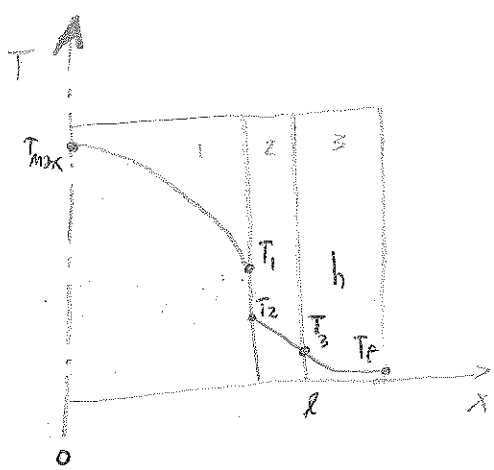
F82H properties (steel)

$\rho = 8055\ kg/m^3$

$c_p = 480\ J/kg/K$

$K = 15.1\ W/m/K$

qualitatively



heat equation

$$\frac{\partial^2 T}{\partial x^2} + \frac{q'''}{K_1} = \cancel{\frac{1}{\alpha}\frac{\partial T}{\partial t}} \qquad \text{region 1}$$

$$\frac{\partial^2 T}{\partial x^2} = 0 \qquad \text{region 2}$$

BC:

2-3 interface: convection

$$-K \left.\frac{\partial T}{\partial x}\right|_l = h\left(T_3 - T_F\right) = q''_w$$

water (3)   I assume liquid water at 82 bar

$Pr = 0.94$ $\rho = 718.4\ kg/m^3$ $\mu = 9.1 \times 10^{-5}\ \frac{Ns}{m^2}$ or $\frac{kg}{ms}$

$Re_D = \frac{V D_h}{\nu} = \frac{\rho V D_h}{\mu} = 3.94 \times 10^5$ turbulent

$k = 0.548\ W/mK$

Dittus Boelter $(Re_D > 10^4)$

$Nu_D = 0.023 Re_D^{0.8} Pr^{0.4} = 673$ $Nu_D = \frac{h D_h}{k}$ $h = Nu_D * k / D_h = 3.69 \times 10^4\ \frac{W}{m^2 K}$

q''' deposited in the breeder zone

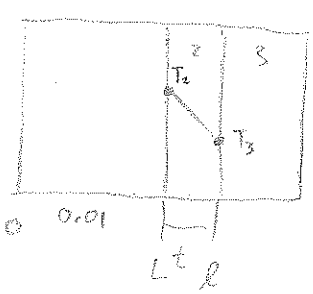
$\Downarrow$

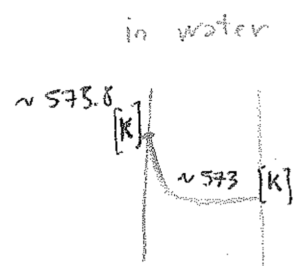
$$q''_w = q''' l = h(T_3 - T_f) \qquad l = 0.01 + 0.003 = 0.013\ m$$

$$T_3 = \frac{q''' l}{h} + T_f = 8 \times 10^6 \left[\frac{W}{m^3}\right] \times 0.013[m] \cdot \frac{1}{3.69 \times 10^4 \left[\frac{W}{m^2 K}\right]} + 573\ [K] = 575.8\ [K]$$

Ferritic steel (2)

$$\frac{\partial^2 T}{\partial x^2} = 0$$





$$T = c_1 x + c_2$$

$$T(x = l) = T_3$$

$$T_3 = c_1 l + c_2 \Rightarrow c_2 = T_3 - c_1 l$$

$$\boxed{T(x) = c_1 (x - l) + T_3}$$

Pebble (1)

$$\frac{\partial^2 T}{\partial x^2} = -\frac{q'''}{k_p} \qquad \frac{\partial T}{\partial x} = -\frac{q'''}{k_p} x + c_3 \qquad T = -\frac{q''' x^2}{2 k_p} + c_3 x + c_4$$

by symmetry $\left.\frac{\partial T}{\partial x}\right|_0 = 0 \Rightarrow \boxed{c_3 = 0}$ $\boxed{T(x) = -\frac{q''' x^2}{2 k_p} + c_4}$

$$T_{F82H}(x) = c_1 (x-\ell) + T_3 \longrightarrow T_{F82H}(x=L) = c_1 (L-\ell) + T_3$$

$$T_p(x) = -\frac{q''' x^2}{2K_p} + c_4 \longrightarrow T_p(x=L) = -\frac{q''' L^2}{2k_p} + c_4 = 25 + c_1(L-\ell) + T_3$$

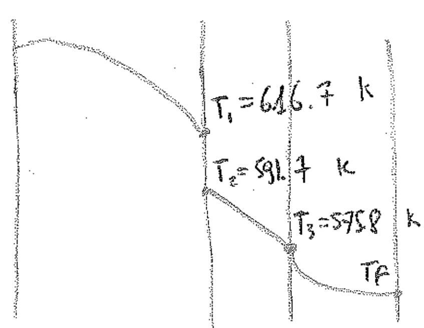
$$\frac{\partial T_p}{\partial x} = -\frac{q'''}{k_p} x \qquad \left.\frac{\partial T_p}{\partial x}\right|_L = -\frac{q''' L}{k_p}$$

$$\frac{\partial T_{F82H}}{\partial x} = c_1 = -\frac{q''' L}{K} = -q''/k$$

$$T_{F82H}(x) = -\frac{q''' L}{K_{F82H}} (x-\ell) + T_3 \qquad \text{for } x=L$$

$$T_2 = T_{F82H}(L) = -\frac{q''' L}{K_{F82H}} (L-\ell) + T_3 = -\frac{q''' L^2}{K_{F82H}}\left(1-\frac{\ell}{L}\right) + T_3 =$$

$$= -\frac{8\times10^6 \times 0.01^2}{15.1}\left(1-\frac{0.013}{0.01}\right) + 575.8 = 591.7\ [k]$$



$$\Rightarrow T_1 = T_2 + 25 = 616.7\ [k]$$

therefore in pebble @ $x=L$

$$T(L) = -\frac{q''' L^2}{2k_p} + c_4 = T_1 \qquad c_4 = T_1 + \frac{q''' L^2}{2k_p}$$

$$\boxed{T(x) = -\frac{q''' x^2}{2k_p} + \frac{q''' L^2}{2k_p} + T_1} = -\frac{q''' L^2}{2k_p}\left[\frac{x^2}{L^2} - 1\right] + T_1$$

$$T_{max} = T(x=0) = \frac{q''' L^2}{2k_p} + T_1$$

k_p for helium at high temperature is 1 $\left[\frac{W}{mk}\right]$ empirically

$$T_{MAX} = \frac{8\times10^6 \times 0.01^2}{2\times 1} + 616.7 = 1016.1 [k]$$

b) $L = 1\,m$ tall for $\bar{U} = 1, 5, 10$ cm/s $d_p = 0.001m$

$T_{m,purge} = 600°C$

random packing of spheres $\phi = 1-\varepsilon = 0.645$ $\varepsilon = 0.355$ $\mu = 416 \cdot 10^{-7}$

$$\frac{\Delta p}{L} = \frac{180\,\bar{U}\,\mu\,(1-\varepsilon)^2}{d_p^2\ \varepsilon^3}$$

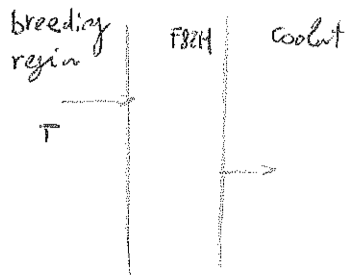
ε void fraction

d_p = particle diameter

	$\bar{U} = 0.01$ m/s	$\bar{U} = 0.05$ m/s	$\bar{U} = 0.1$ m/s
Δp [kPa]	0.692	3.46	6.93

e)

M.Riva



$\bar{U} = 1, 5, 10$ cm/s

$\dot{m}_T = 1.21\,e{-7}$ g/s

$T_{bed} = 600\,°C = 873\,K$

$$\left(\begin{array}{l} \nabla \cdot \vec{J} = \dot{S} \\ \nabla \cdot \left(-D_i \nabla C_i\right) = \dot{S} \end{array} \right)$$

$D = 8.76 \cdot 10^{-4} \exp\left(-0.1446 / k_B T_{bed}\right)$

$k_B = 8.6167 \cdot 10^{-5}$ eV K^{-1}

$D = 1.278 \times 10^{-4}$ cm^2/s $= 1.278 \cdot 10^{-8}$ $\frac{m^2}{s}$

$P_m = D\,S$

Permeation flux

$$J_p = \frac{P_m}{t_m} \sqrt{P_T} = \frac{D \cdot S}{t_m} \sqrt{P_T} \qquad \frac{\frac{m^2}{s} \cdot \frac{mol}{m^3 \sqrt{Pa}} \sqrt{Pa}}{m} = \frac{mol}{m^2 s}$$

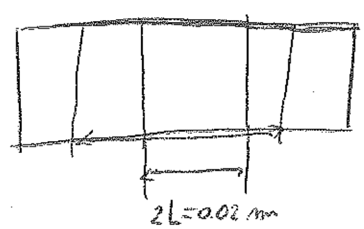
$S = 0.3638 \exp\left(-0.2773 / k_B T_{bed}\right) =$

$= 9.12 \cdot 10^{-3}\, mol/m^3 \sqrt{Pa}$

t_m is 0.003 m $= t_{F82H}$

$$P = \dot{m}_t \cdot R\,T_{bed} / V_{bed} \qquad \frac{kg}{s} \cdot \frac{J}{kg\,K} \cdot K \cdot \frac{s}{m^3} = \frac{J}{m^3} = Pa$$

V_{bed} volumetric flow rate per unit of length,



$$V_{bed} = \bar{U} \cdot 2L = \begin{cases} 2 \cdot 10^{-4} = V_{1bed} \\ 1 \cdot 10^{-3} = V_{2bed}\ m^2/s \\ 2 \cdot 10^{-3} = V_{3bed} \end{cases}$$

$R_{He} = 2078$ J/kg K

$$P_{T1} = 1.21\,e{-7} \left[\frac{g}{s}\right] \cdot 10^{-3} \left[\frac{kg}{g}\right] \cdot 2078 \left[\frac{J}{kg\,k}\right] \cdot 873\,[k] \Big/ 2 \cdot 10^{-4} \left[\frac{m^2}{s}\right] = 1.09\ Pa$$

P_{T1} for V_{1bed}

P_{T2} for V_{2bed}

P_{T3} for V_{3bed}

$P_{T2} = 0.21$ Pa $\qquad P_{T3} = 0.109$ Pa

	U_1	U_2	U_3
J_p $\left[\frac{mol}{m^2 s}\right]$	4.06×10^{-8}	$1.78 \cdot 10^{-8}$	1.28×10^{-8}

$$J_p = \frac{D \cdot S}{t_w} \sqrt{\frac{p}{\tau}}$$