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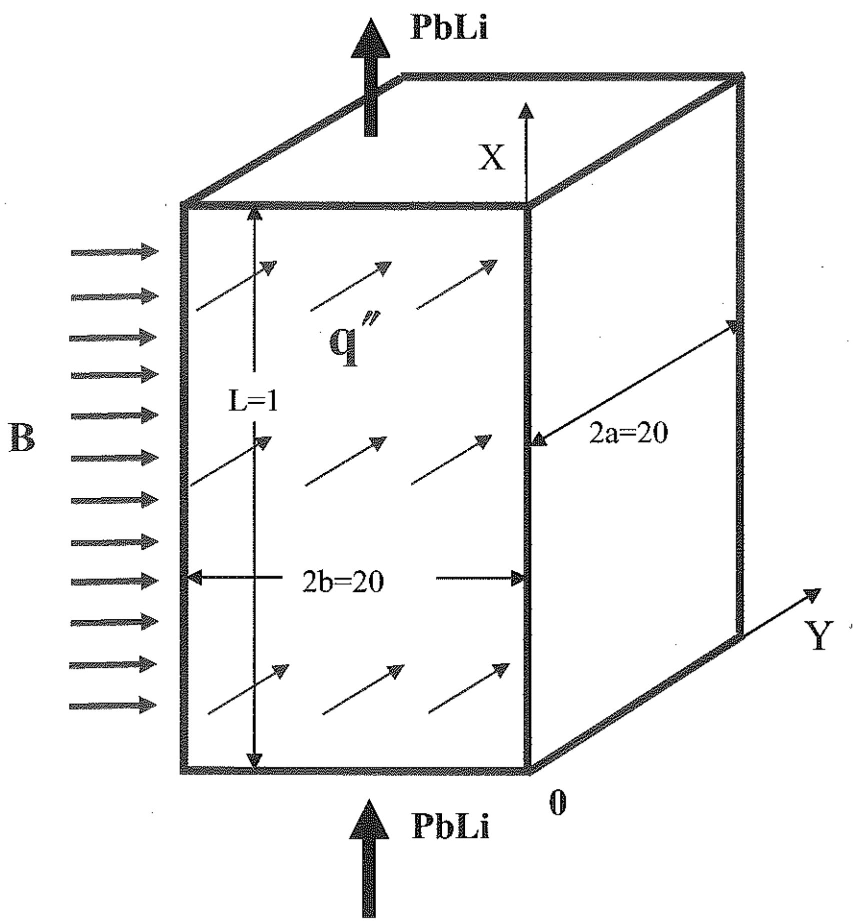
- **Include the details of your solutions**
- **Provide informal citations for any sources used**
- **Make, indicate, and justify any significant assumptions**
- **Please work independently**

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.



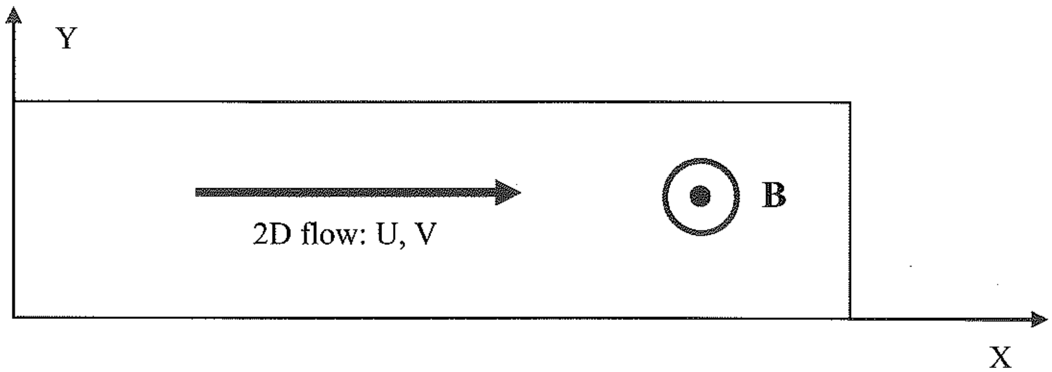
Physical properties

Fe: $\sigma=1.4\times10^{6}$ 1/Ohm-m, k=33 W/m-K, ρ=7800 kg/m3, C_p=750 J/kg-K

PbLi: $\sigma=0.7\times10^{6}$ 1/Ohm-m, k=15 W/m-K, ρ=9300 kg/m^3, C_p=190 J/kg-K, μ=0.001 Pa-s

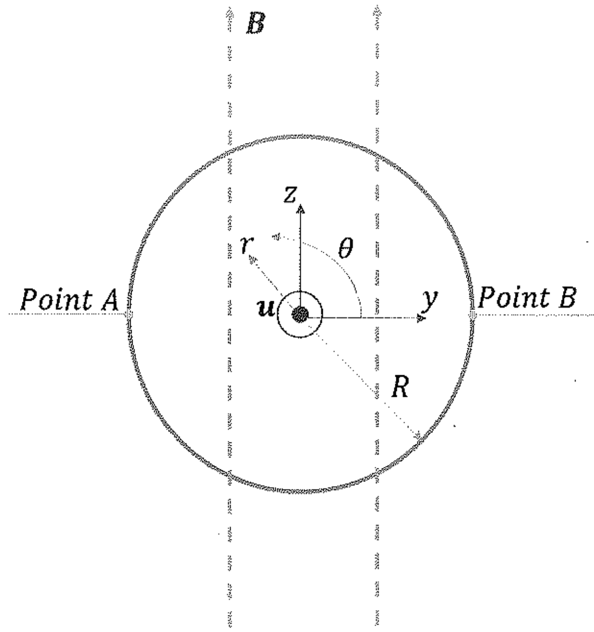
Problem 2

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 ($\boldsymbol{B} = B\hat{e_z}$) 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 $\boldsymbol{u}(r) = 2u_{avg}\left(1 - \frac{r^2}{R^2}\right)\hat{e_x}$ (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.

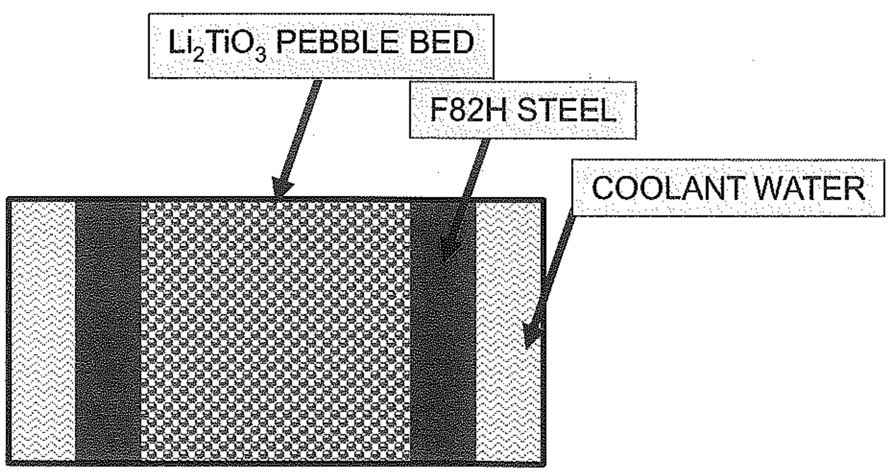
Problem 8

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.



Problem #1

a) $Ha = B_o b \sqrt{\frac{\sigma}{\mu_{fl}}} = (5)(0.1)\sqrt{\frac{7e5}{.001}} \rightarrow \boxed{Ha = 1.32e4}$

$Re = \frac{U_{avg}\, a}{\nu} = \frac{U_{avg}\, a}{\mu/\rho} = \frac{(0.5)(0.1)}{(.001/9300)} \rightarrow \boxed{Re = 4.65e5}$

$Re_m = \frac{U_{avg}\, a}{\eta} = \frac{U_{avg}\, a}{1/\mu_o\sigma_{fl}} = U_{avg}\, a\, \mu_o \sigma_{fl} = (0.5)(0.1)(4\pi e{-7})(7e5) \rightarrow \boxed{Re_{,m} = 0.044}$

$N = \frac{Ha^2}{Re} = \frac{(1.32e4)^2}{4.65e5} \rightarrow \boxed{N = 374.7}$

$C = \frac{\sigma_w t_w}{\sigma_{fl}\, b} = \frac{(1.4e6)(.002)}{(0.7e6)(0.1)} \rightarrow \boxed{C = 0.04}$

b) without insulation

Will have MHD pressure drop b/c current conducts through wall

N-S MHD: $\cancel{\frac{\partial \bar{u}}{\partial t}}^{0} + \cancel{(\bar{u}\cdot\nabla)\bar{u}}^{0} = -\frac{1}{\rho}\nabla p + \cancel{\nu\nabla^2\bar{u}}^{0} + \frac{1}{\rho}(\bar{J}\times\bar{B}) \longrightarrow \frac{1}{\cancel{\rho}}\nabla p = \frac{1}{\cancel{\rho}}\bar{J}\times\bar{B}$

S.S. ignore viscous effects

Ohm's Law: $\bar{J} = \sigma_{\cdot}(\cancel{\bar{E}}^{0} + \bar{u}\times\bar{B}) = \sigma UB \longrightarrow \bar{J}\times\bar{B} = \underline{\sigma_f UB^2}$

$\rightarrow \underline{\nabla p = \sigma_f UB^2}$. Note that this assumes all resistance comes from the fluid, actually it is expressed as $\sigma_{fl}\cdot C$, the conductance ratio:

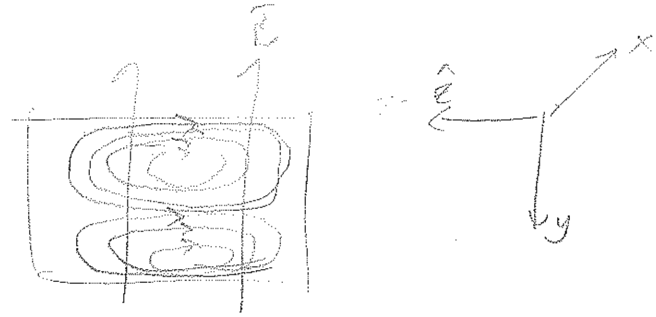
$\rightarrow \nabla p = \frac{\Delta p}{\Delta L} = \sigma_{fl} UB^2 C \longrightarrow \Delta p = L\sigma_{fl} U_{avg} B_o^2 C = (1)(7e5)(0.5)(5^2)(.04)$

$\therefore \boxed{\Delta p = 3.5e5\ Pa = 50\ psid}$

with insulation

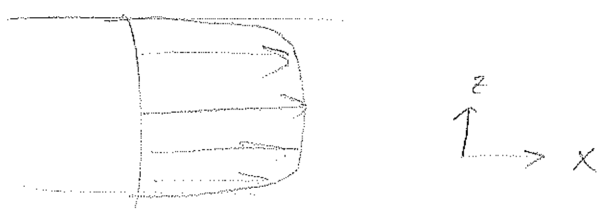
There are no MHD pressure losses if all the induced current resides in the fluid, since all body forces from $J_{induced} \times B$ would sum to 0. $\rightarrow$ $\boxed{\Delta p_{MHD} = 0}$

c) Shape of velocity profile

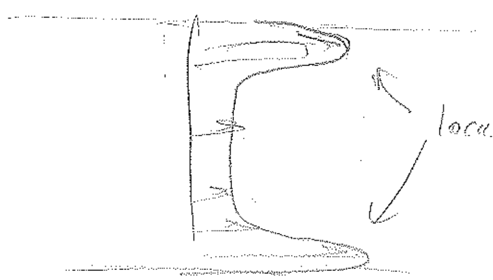


without insulation

Hartmann profile in z

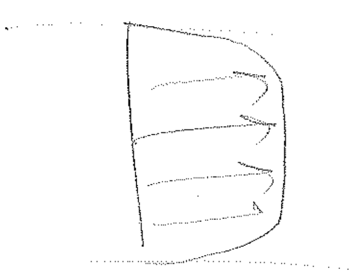


"m-shaped" profile in y

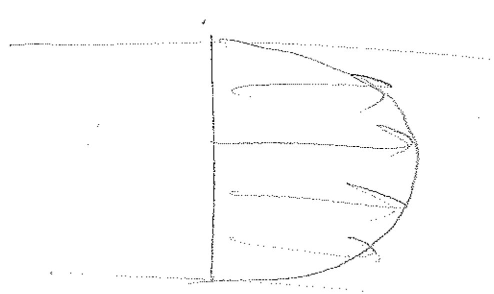


with insulation

Hartmann profile in z



Laminar viscous profile in y
parabolic



d) Turbulent regime occurs when $R = \frac{Re}{Ha} > 200$

$$R = \frac{4.65e5}{1.32e4} = \underline{35} < 200 \longrightarrow \therefore \boxed{\text{Laminar flow}}$$

e) Estimate $T_{out} - T_{in}$

Assumptions: 1) Treat volumetric heating as avg vol. heating across tube
2) Treat surface heat flux as if it were evenly distributed across the tube cross-section
3) Neglect thermal losses from tube other than convection to the fluid. If other losses are considered the ΔT would be less.

For a constant heat flux, we use conservation of energy to get global temp change

$$\underbrace{q''_s L(2b)}_{\text{surface heat flux} = P_{FW}} + \underbrace{q'''_{eff} \forall}_{\text{volumetric heat flux} = P_{vol}} = \dot{m} c_p \Delta T \qquad \text{(From any heat transfer text)}$$

$\dot{m}$: mass flowrate of fluid

Get effective q''':

$$q'''_{eff} = \frac{\int_0^{2a} q'''(y)dy}{2a} = \frac{1}{2a}\int_0^{2a} 30e6\, e^{-y/0.1} dy = \left(\frac{1}{0.2}\right)\left(\frac{-1}{10} e^{-10y}\right)\Big|_0^{0.2} = \underline{1.3e7\ W/m^3}$$

$$P_{vol} = q'''_{eff}\forall = (1.3e7\ W/m^3)(0.2)(0.2)(1)\,m^3 = \underline{5.25e5\ W}$$

Surface heat:

$$P_{FW} = q'' L 2b = (0.5\ MW/m^2)(1m)(0.2m) = \underline{1e5\ W} \quad \text{much less than } P_{vol}$$

Get $\dot{m}$: $\dot{m} = \rho \dot{\forall} = \rho(2a)(2b)U = (9300)(0.2)^2(0.5) = \underline{186\ kg/s}$

Solve: $$\Delta T = \frac{P_{FW} + P_{vol}}{\dot{m} c_p} = \frac{5.25e5 + 1e5}{(186)(190)} \Rightarrow \boxed{\Delta T = 17.7\ K}$$

seems low, but PbLi has a lot of thermal mass and is barely flowing.

Problem #2

The vorticity comes from taking the curl of the MHD fluid momentum equation.

$$\text{MHD mom:}\quad \frac{\partial \bar{u}}{\partial t} + (\bar{u}\cdot\nabla)\bar{u} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\bar{u} + \underbrace{\frac{1}{\rho}(\bar{J}\times\bar{B})}_{\text{Lorentz body force term}}$$

This is essentially the Navier-Stokes equation with an extra term for the Lorentz force caused by the induced electric current.

Taking the curl:

$$\nabla\times NS \Rightarrow \underbrace{\nabla\times\frac{\partial\bar{u}}{\partial t}}_{①} + \underbrace{\nabla\times\left[(\bar{u}\cdot\nabla)\bar{u}\right]}_{②} = \underbrace{\nabla\times\left[-\frac{1}{\rho}\nabla p\right]}_{③} + \underbrace{\nabla\times\left[\nu\nabla^2\bar{u}\right]}_{④} + \underbrace{\nabla\times\left[\frac{1}{\rho}(\bar{J}\times\bar{B})\right]}_{⑤}$$

① $= \frac{\partial}{\partial t}(\nabla\times\bar{u})$, which, using the definition $\bar{\omega}\equiv\nabla\times\bar{u}$ gives $\frac{\partial\bar{\omega}}{\partial t}$

② $(\bar{u}\cdot\nabla)\bar{u} = \nabla(\frac{1}{2}\bar{u}\cdot\bar{u}) - \bar{u}\times(\nabla\times\bar{u}) = \nabla(\frac{1}{2}|\bar{u}|^2) - \bar{u}\times\bar{\omega}$

Taking curl $\Rightarrow$: $\underbrace{\nabla\times\left[\nabla(\frac{1}{2}|\bar{u}|^2)\right]}_{\text{curl(grad) of scalar fcn}=0} - \nabla\times(\bar{u}\times\bar{\omega}) = -\nabla\times(\bar{u}\times\bar{\omega})$

③ $\nabla\times(-\frac{1}{\rho}\nabla p) = \underbrace{-\frac{1}{\rho}(\nabla\times\nabla p)}_{\text{curl(grad)}=0} + \nabla(-\frac{1}{\rho})\times\nabla p = \frac{\nabla\rho\times\nabla p}{\rho^2}$

④ Assume $\nu = \text{const} \rightarrow\ = \nu\left[\nabla\times\nabla^2\bar{u}\right]$

⑤ $= \nabla\times\frac{1}{\rho}(\bar{J}\times\bar{B})$

$\Rightarrow$ full vorticity eq: $\therefore$ $$\boxed{\frac{\partial\bar{\omega}}{\partial t} = \nabla\times(\bar{u}\times\bar{\omega}) + \frac{\nabla\rho\times\nabla p}{\rho^2} + \nu(\nabla\times\nabla^2\bar{u}) + \nabla\times\left(\frac{\bar{J}\times\bar{B}}{\rho}\right)}$$

MHD effects: Vortexes will form and diffuse throughout the domain. Ignoring viscosity, assuming incompressible, and treating steady state gives:

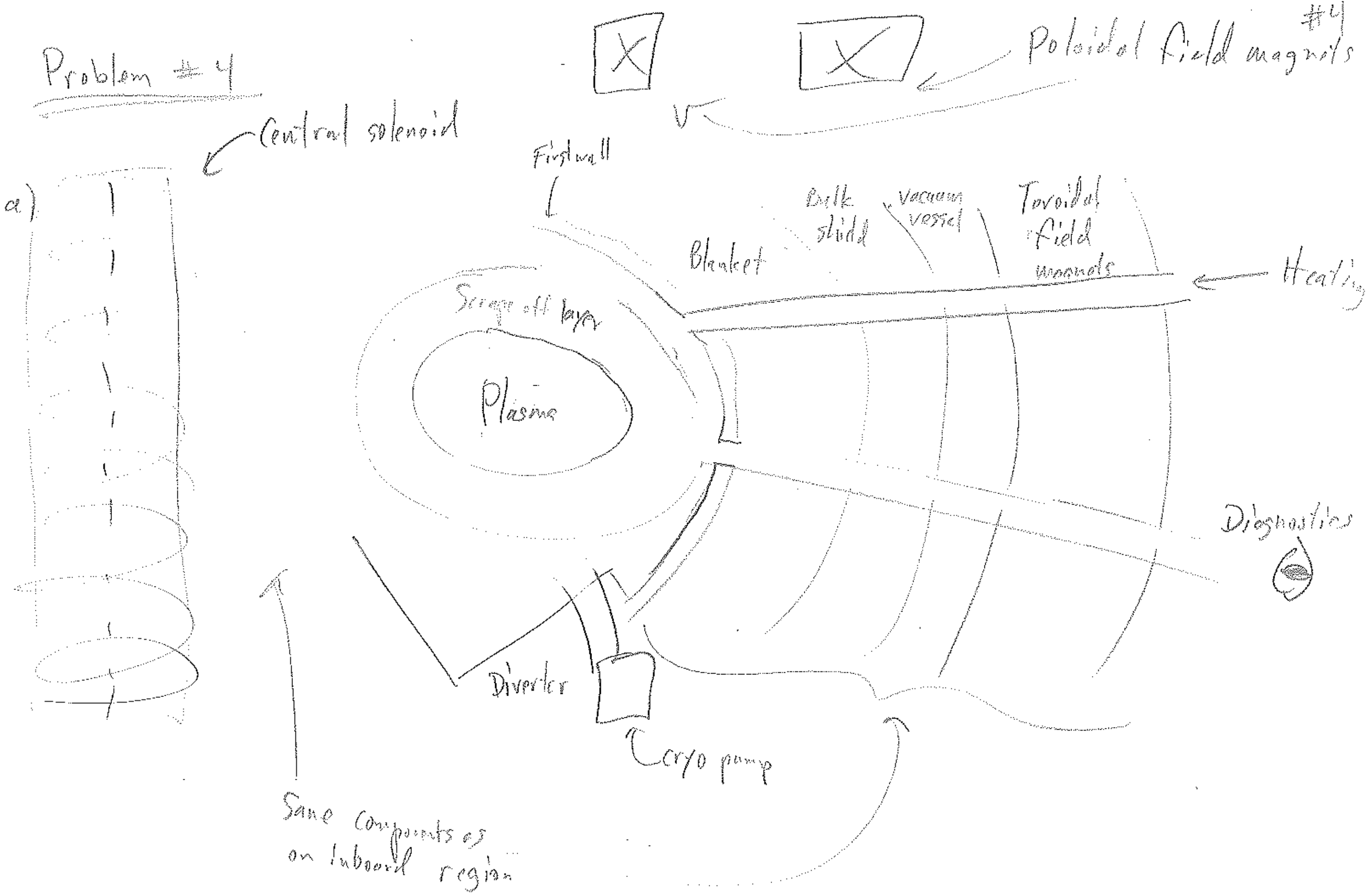
$$\nabla\times(\bar{u}\times\bar{\omega}) = -\frac{1}{\rho}\nabla\times(\bar{J}\times\bar{B}) \rightarrow \bar{u}\times\bar{\omega} = \underbrace{-\frac{\bar{J}\times\bar{B}}{\rho}}_{\text{Lorentz force}}$$

$\rightarrow$ Lorentz body force causes "swirling".

#4

Problem #4

a)



b) Plasma - Produces high energy neutrons and α-particles.

Scrape-off layer - Edge region of plasma that accumulates He "ash" and impurities that are transported to the divertor (via mag. fields) for removal.

First wall - Absorbs radiation from plasma & protects blanket.

Blanket - Serves two purposes: tritium breeding and heat removal, which ultimately is used for generating electricity through a conversion to steam and passage through turbine-generator

Bulk Shield - Protects superconducting magnets from neutron and radiation damage.

Vacuum Vessel - Provides seal against air.

Toroidal Field Magnets - Generate toroidal magnetic field to confine plasma radially.

Poloidal Field Magnets - Generate poloidal magnetic field to shape plasma such that it has the correct curvature and directs particles in the scrape-off-layer to the divertor.

Central Solenoid - Induces toroidal electric field that drives a toroidal current. This current both heats the plasma and induces a poloidal magnetic field to keep drifts (due to $\vec{B}$ field gradient and curvature) to a minimum.

Diverter - Collects a large percentage of α-particles and impurities to remove from plasma (which serves as an energy sink). It absorbs a larger heat flux than the first wall.

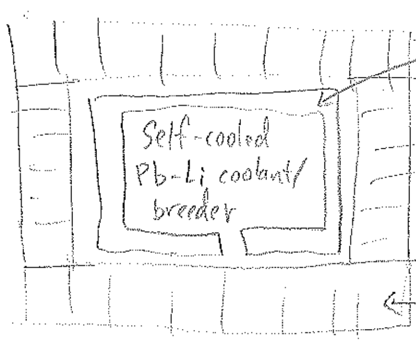
Cryopumps - Remove gases leaking into vacaum vessel, impurities, and unused fuel (D & T).

Heating - Devices that inject energy into plasma (NBI, microwave, etc.)

Diagnostics - Devices that provide info on plasma properties.

c) Compared to the other major toroidal confinement device (stellerator), the tokamak generates the poloidal (helical) magnetic field using a toroidal current. The stellerator twists the external magnets in such a way as to provide the same effect as the toroidal current in tokamaks. For this reason the tokamak is simpler in construction but is more complicated because of the systems needed to drive the toroidal current.

d)



Composite flow channel insert to thermally insulate the breeding zone (SiC_f/SiC composite), also to provide electrical insulation to minimize MHD pressure drop

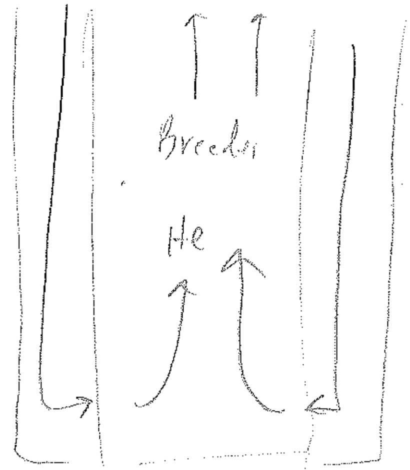
He cooled structure, ferritic steel

e)

	DCLL	Separately - Cooled PbLi
Features	Breeding zone self cooled Liquid metal MHD breeder	Separate region for liquid metal breeder He cools both regions, separately. All thermal energy extraction uses He.
Advantages	Thermal insulation improves efficiency Low tritium partial pressure Not limited to max temp of structure b/c of insulation	Higher MHD effects
Disadvantages	MHD effects (complicated, high pressure drop) Complicated buoyancy effects	High tritium partial pressure → tritium permeation T_{out} limited by PbLi compatibility w/ RAFM (~470°C max), so lower thermal efficiency MHD effects Requires advanced structural materials

c) Tritium extraction

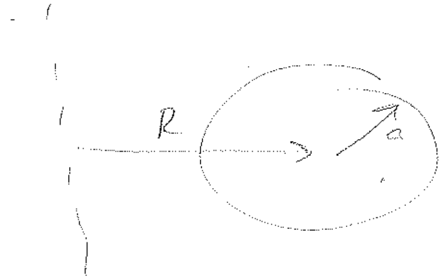
Tritium released from the breeding material, is entrained by a low flow rate, low pressure purge gas consisting of He w/ some H_2 to promote tritium release from the breeder.



Tritium becomes either HTO (liquid) or as a gas.
The liquid is separated using a molecular sieve. The gas is collected using a cryogenic molecular sieve, then the H isotopes desorbed by warming.

Problem #5

a) Get P_{fus}



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

$P_N = P_{NW} \cdot A_{wall}$; $A_{wall} = \pi^2\left[(R+a)^2 - (R-a)^2\right] = \underline{660\ m^2}$

$P_N = (3.6\ MW/m^2)(660\ m^2) = \underline{2{,}374\ MW}$

$P_{fus} = P_N\left(\frac{17.58}{14.16}\right) \Rightarrow \boxed{P_{fus} = 2{,}969\ MW}$

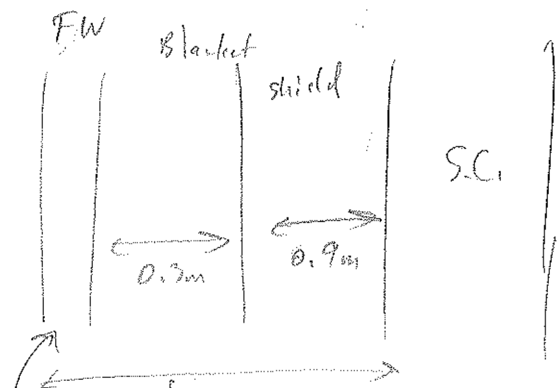
b) Neutrons into S.C.

$P_{N,blanket} = \left(\frac{1}{100}\right)P_N = 29.7\ MW$

$P_{N,shield} = P_{N,blanket}\, e^{-(0.0977\,cm^{-1})(90\,cm)}$
$= \underline{4.5\ kW}$

∴ If we ignore α-power, the heat load into the cryogenic system is : $\boxed{P_{s.c.} = 4.5\ kW}$

I assume a 0.3 m blanket based on HW#5



$\Delta^i_{BS} \approx \Delta r_{blkt} + \Delta r_{shield} = 1.2\,m$

(assume Δr_{fw} is ~1-5 mm which is small compared to blkt & shield)

Gamma Rays

Need α-power : $P_\alpha = P_{fus} - P_N = \underline{595\ MW}$

Assume 60% goes to the divertor : $P_{\alpha,fw} = (0.4)P_\alpha = \underline{238\ MW}$

Assume a ceramic breeder made predominantly of BeO (breeder), we can calc the attenuation through the blanket using the mass attenuation const :

$P_{\gamma,shld} = P_{\gamma,blkt}\, e^{-\mu \Delta r_{blkt}}$, $\Rightarrow P_{\gamma,s.c.} = P_{\gamma,shield}\, e^{-(0.1008\,cm^{-1})(90\,cm)}$

energy attenuation for γ-rays in shield

$P_{\gamma,shield} \cdot 1e\text{-}4$

∴ Need μ_{BeO} to calculate this, but should also account for first wall and attenuation by other materials.

→ Add this to neutron power to get total heat load needed to be removed from the s.c. mass.

∴ $\boxed{P_{rem,s.c.} = P_{N,s.c.} + P_{\gamma,s.c.}}$

c) Assume maximum reverse Carnot efficiency:

$$P_{electrical} = \frac{P_{rem,s.c.}}{\eta_{cool}} = \frac{P_{rem,s.c}}{\frac{T_c}{T_h - T_c}} \quad \text{where} \quad \begin{array}{l} T_c = \sim 4K \text{ (cryo S.C. mass)} \\ T_h = \sim 293K \text{ (room temp)} \end{array}$$

Since I didn't calculate γ-ray power into S.C., I'll use the neutron power instead

$$= \frac{4.5\,kW}{4/(293-4)} \rightarrow \boxed{P_{electrical} = 325\,kW}$$

d) The max $\vec{B}$-field occurs on the inboard wall. I assume a peaking factor of $K_{peak} = 1.4$ based on Handout #1, and assume this occurs on the inboard wall. Note this is not true for the D-shape profile showed in the handout so this is pretty arbitrary. Need to know exact neutron wall load for this assumed circular cross-section to be exact.

Wall loading at S.C.:

$$P_{N,SC,W} = \frac{P_{N,S.C}}{A_{S.C}} \qquad A_{S.C.} = \pi^2\left[(R + a + \Delta^i_{BS})^2 - (R - a - \Delta^i_{BS})^2\right] = 931\,m^2$$

$$\rightarrow \quad P_{N,S.C.,W} = \frac{4.5\,kW}{931\,m^2} = 4.83\,kW/m^2$$

The integrated wall loading for 4 yrs $\longrightarrow$ $P_{SC,W} = 19.32\,kW\text{-}y/m^2$ $\leftarrow$ this is avg.

The max integrated wall loading will be K_{peak} times higher: $\underline{P_{SC,w,max} = 27\,kW\text{-}y/m^2}$

Using the table on Handout #13, slide 21, for $\Delta^i_{BS} = 1.2\,m$, to be

$$\therefore \quad \boxed{\rho_r \approx 5e\text{-}10\,\Omega\text{-cm}}$$

Note: This assumes that the ρ_r given in the table was not assuming any attenuation by the first wall, blanket, or shield. If this is inaccurate the the assumed attenuation (total) used in the table would need to be compared to the attenuation I assumed in my calcs earlier.

e) Get rate of tritium production:

$$TBR = 1.15 = \frac{\text{tritium production}}{\text{tritium consumption}} = \frac{\dot{t}_p}{\dot{t}_c}$$

$\underline{\dot{t}_c}$

$$P_{fus} = E_{DT,\,reaction} \cdot rate \rightarrow Rate = \frac{P_{fus}}{E_{D\text{-}T}} = \frac{(2969\,e6\,\cancel{J}/s)}{(17.58\,\cancel{MeV})(1.6\,e\text{-}13\,\cancel{J}/\cancel{MeV})} = \underline{1.06e21\,/s}$$

$$\dot{t}_c = Rate \cdot m_t = (1.06e21)(5.0083\,e\text{-}27\,kg/t) = \underline{5.31\,e\text{-}6\ kg/s}$$

$$\dot{t}_p = TBR \cdot \dot{t}_c = (1.15)(5.31e\text{-}6) \rightarrow \boxed{\dot{t}_p = 6.11\,e\text{-}6\ kg/s}$$

Problem # 6

a) S.C. magnets operate at very low temps (<10K) to stay superconducting. The S.C. wires are embedded in a copper stabilizer (typically) to conduct away any excess heat applied to the S.C. coil. The S.C. temp cannot rise > 0.2 K, otherwise it will cause an increase in $\rho_{S.C.}$ which increases the temp, etc., resulting in a runaway and loss of superconductivity. So the Cu stabilizer needs to rapidly dissipate heat. The criterion is $\boxed{I^2 \rho \le q P a}$ ← radius. Because of the high thermal conductivity of Cu, heat is transferred rapidly to the He coolant.

heat flux to the coolant

perimeter

b) Dislocations of S.C. component material lattice sites from neutrons will affect many of the mat'l properties, one of which is resistivity. This happens to both the S.C. and Cu stabilizer. Eventually, with enough dislocations, the electrical resistance can become high enough to prevent superconductivity.

Other effects of radiation include:

- Gas production (He & H_2) from α-particle implantation
- Transmutation of non-radioactive mat'l to radioactive material that leads to safety risk
- Reduction of dielectric coefficient, ε, of electrical insulators. Depends on mat'l (inorganic, epoxy, Mylar)
- Physical deterioration of organic insulators.
- Reduction of ductility (i.e. embrittlement)

c) Bulk shielding – Protects vacuum vessel and S.C. magnets. Surrounds blanket.

Penetrative shielding – Protects objects that protrude through vacuum vessel to plasma, such as:
- Neutral beam injectors
- Antennae for launching waves to heat plasma
- Optical ports for spectroscopical measurements or imaging
- Vacuum pump ports

Biological shielding – Protects personnel in building. Typically made of concrete and serves dual purpose as building walls.

d) Bulk shield – Stainless steel with $^{10}B_4C$. This minimizes energy leakage due to having a balance of high-Z mat'l (for neutron energy attenuation), low-Z mat'l (for slowing down med/low energy neutrons), and because it is a strong absorber of neutrons while at the same time emitting a minimum amount of γ-rays.

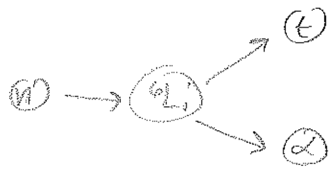
First Wall – Tungsten alloys for high melting temp and low sputtering coefficient. However, liquid metal walls (such as FLiNaBe) are being researched.

Reduced Activation Ferritic/Martensitic (RAFM) is being considered for use due to its low radioactivity compared to conventional stainless steel.

Problem # 7

↙ * Masses from Wikipedia

a) $^6Li \rightarrow$



$$Q = [M_{reactants} - M_{products}]c^2$$

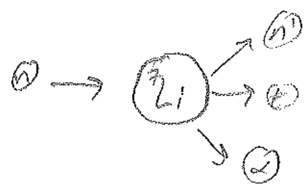
$$= [(m_{Li6} + m_n) - (m_t + m_\alpha)]c^2$$

$$= [(1.6749e{-27} + 9.9854e{-27}) - (5.007e{-27} + 6.645e{-27})] \times (3e8)^2$$

$$= 7.662e{-13}\ J \times 1.6e{-13}\ \frac{MeV}{J}$$

$$\therefore \boxed{Q = 4.78\ MeV}$$

$^7Li \rightarrow$



$$Q = [(m_{Li7} + m_n) - (m_n + m_t + m_\alpha)]c^2$$

$$= [(1.165e{-26} + 1.675e{-27}) - (1.675e{-27} + 5.007e{-27} + 6.665e{-27})] \times (3e8)^2$$

$$= -3.953e{-13}\ J \times 1.6e{-13}\ MeV/J$$

$$\therefore \boxed{Q_{Li7} = -2.47\ MeV}$$

b) The heating locally is from the charged α-particle, so we need to know the energy transferred to it. From HW #2, the energy of the scattered neutron is:

$$E_N' = \frac{E}{(1+A)^2}\left[\cos\alpha + \sqrt{A^2 - \sin^2\alpha}\right]^2$$ where E = incident angle, $A = \frac{M_A}{M_N}$, α = scattering angle

$$A = \frac{M_A}{M_N} = \frac{9.9856e{-27}\ kg}{1.6749e{-27}\ kg} = 5.96 \quad ; \quad \alpha = 45^\circ, \ E = 1\ MeV$$

$\alpha = 45^\circ$

→ Calculator → $E_N' = 0.9061\ MeV$ most of the energy still contained in the neutron

$$\therefore \boxed{E_{Li6}' = 1 - E_N' = 0.094\ MeV \text{ heat per interaction}}$$

c) $Q = -5$ MeV , 14 MeV neutrons

$K_n = N k_n$, where $k_n = \sum_i \sigma_i(E) E_{H_i}$.

↑ macroscopic kerma factor

$E_{H_i} = E_n - E_{n'} + Q$

$= 14 \text{ MeV} - 0 - 5 \text{ MeV} \rightarrow \boxed{E_H = +9 \text{ MeV}}$

Need to know what this nuclide is to get $\sigma(E)$ (the cross-section) and N (the density)

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

$E = E_0 e^{-\mu_{tot} \Delta r} \longrightarrow \frac{E}{E_0} = e^{-\mu_{tot}\Delta r} \xrightarrow{\ln()} \ln\left(\frac{E}{E_0}\right) = -\mu_{tot}\Delta r$

$\Delta r = \frac{\ln(E/E_0)}{-\mu_{tot}} = \frac{\ln(1e-4)}{-0.138} \rightarrow \boxed{\Delta r = 66.74 \text{ cm}}$

e) NTE: $\underbrace{\frac{\partial n}{\partial t}}_{\text{rate of change of neutrons with a specific energy}} + \underbrace{v\hat{\Omega}\cdot\nabla n}_{\text{leakage out of volume}} + \underbrace{v\Sigma_t n(\vec{r}, E, \hat{\Omega}, t)}_{\text{loss due to collisions that change energy of neutron}} = \overbrace{\int_{4\pi} d\hat{\Omega}' \int_0^\infty dE' v' \Sigma_s(E' \to E, \hat{\Omega}' \to \hat{\Omega}) n(\vec{r}, E', \hat{\Omega}', t)}^{\text{inscattering: effectively a source of neutrons that were at a different energy but were somehow brought into this energy class}}$

$+ \underbrace{S(\vec{r}, E, \hat{\Omega}, t)}_{\text{neutron sources}}$

The most difficult term to calculate is the inscattering source term.

f1) $TBR = \sum_i rate_i \cdot \#T_i$ atoms generated

Tritium only produced by $^6Li(n, \alpha)$ and $^7Li(n, n'; \alpha)$, with 1 each

$\uparrow$ rate = 0.8 $\quad$ $\uparrow$ rate = 0.4

$\rightarrow$ $TBR = (0.8 \cdot 1) + (0.4 \cdot 1) \longrightarrow \boxed{TBR = 1.2}$

f2) ϵ = energy from neutrons deposited in blanket per fusion neutron / 14.06 MeV.

$= \frac{1}{14.06 \text{ MeV}} \left[0.1 \cdot (-13) + 0.05 \cdot 8 + 0.8 \cdot 4.8 + 0.02 \cdot 5 + 0.4 \cdot (-2.4) \right]$

$\boxed{\epsilon = \frac{2.08 \text{ MeV}}{14.06 \text{ MeV}} = 0.148}$

Seems really low. Is this because of poor neutron multiplication? If beryllium were used would this be improved? What about extracting heat from first wall and shield? why is this not accounted for?

f3) $P_{fus} = 3000$ MW, $\eta_{th} = 0.35$

$P_{electrical} = \underbrace{\text{heat deposited into blanket}}_{P_{blkt}} \cdot \eta_{th}$

$P_{blkt} = P_N \epsilon + P_\alpha$

$P_N = P_{fus} \left(\frac{14.06}{17.58} \right) = 2399.3$ MW

$P_\alpha = P_{fus} - P_N = 600.7$ MW

$\rightarrow$ $P_{blkt} = (2399.3 \text{ MW})(0.15) + 600.7 \text{ MW} = \underline{960.6 \text{ MW}}$

$P_{electrical} = (960.6 \text{ MW})(0.35) \rightarrow \boxed{P_{electrical} = 336.2 \text{ MW}}$ Seems really low