Heat Removal I

Thermodynamics and Divertor

Ben McCrossan

Background

- 1000 MWth output
- 2 Separate Coolants
  - Pb-17Li-Surrounding 1st Wall for Tritium Breeding
  - Pressurized Water-Cooling Divertor, has high specific heat capacity
- Pb-17Li passes through heater exchanger with water
- Pressurized water then used for Rankine Cycle
- Estimated thermodynamic efficiency of 35%

Heat Flux Distribution

- 1000 MWth
  - 800 MWth or 80% leaving through 1st wall
    - 640 MWth or 80% of energy is neutrons
    - 160 MWth of 20% of energy is radiation
    - Distributed over Area of roughly $4\pi^2Ra$
    - Heat Flux: 1.88 MW/m2
  - 200 MWth or 20% leaving through divertor
    - Almost entirely heavy charged Particles(alpha & impurity)
    - Distributed over Area or $2\pi R$*Width
    - Divertor Heat flux: 1.77MW/m2 (Assuming uniform distribution)

Thermodynamics

- Pb-Li17
    - Operating Temperature: 520-720 K
        - Range chosen based on Eutectic melting point of Pb-Li and Temperature limits of structural material(ODS Steel)
- Pressurized Water
    - Operating Temperature: 320-570 K
        - Based on liquid temperature range of pressurized water
        - mimics existing LWR power-cycles

Thermodynamics

Power Cycle

- Rankine steam cycle chosen over gas Brayton cycle
- Rankine is cheaper, Brayton is more efficient
- Water is already being used to cool the divertor, and the heat from the reactor isn't high enough quality (720 K) to justify using a Brayton cycle

Efficiency:

- Carnot Efficiency: $(T_h - T_c)/T_h = 56\%$
- Realistic Efficiency: 35%

Lithium-Water reactivity

- Generally occurs slowly
- Energy of 222 kJ/mol
- Assuming HX length of 10m
- Total energy is .237 TJ
- Equivalent to 56.7 metric tons of TNT
- System temperature increase of 2477K

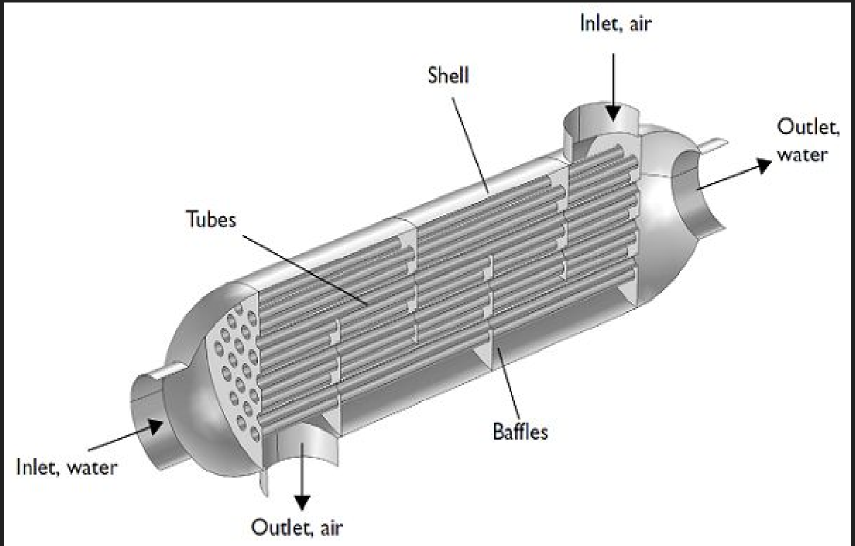
Passive Safety:

Overbuilt tubing-SiC

Active Safety:

Monitor HX temperature

Flush system with helium



Divertor

- Divertor was chosen over Limiter Design
- Separate Chamber with cooled particles translates to less sputtering
- Removes alpha particles & other impurities from plasma
- Also removes significant amount of heat

Material Choice: Tungsten

- Has highest sputtering threshold
- Very high melting point
- Can withstand high heat flux (8 MW/m^2)

Configuration: Single set of plates at bottom of reactor

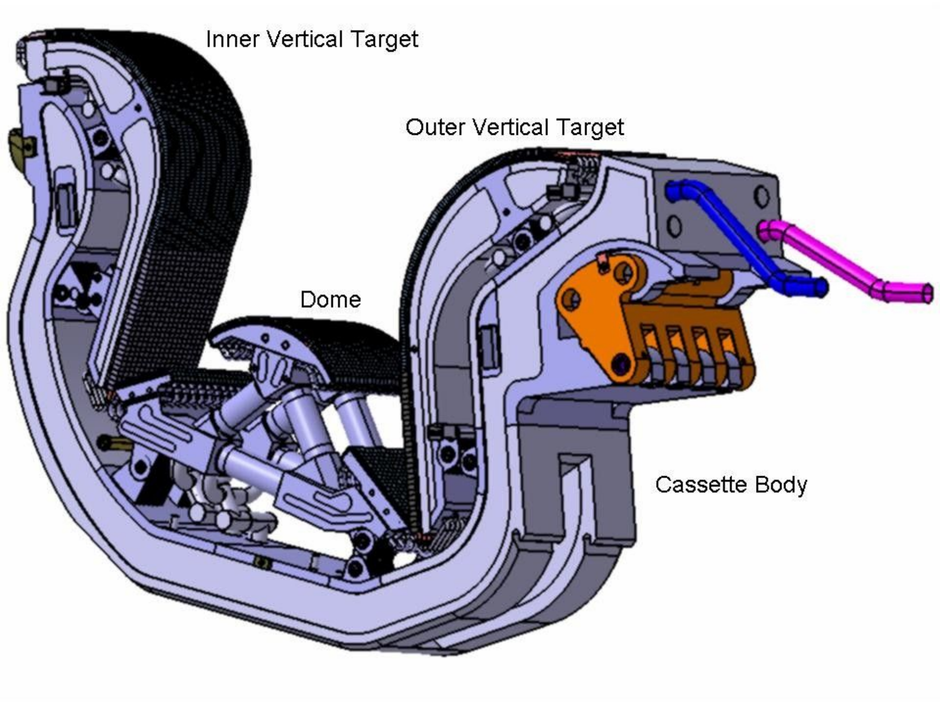
Divertor

Total Heat: 200MW

- Water:
  - Specific Heat: C_p=4.18 kJ/kg-K
  - Temperature Change: ΔT=250 K
  - Mass Flow Rate: m=191.39 kg/s
  - Volumetric Flow Rate: V=.19138 m^3/s
- Cooling Channel
  - Total Cross Section: Area=.127 m^2
  - Coolant Velocity: v=1.507 m/s
  - SiC Tubing-In contact with high temperature tungsten

Divertor

Parameters	Value
#of Tubes	180U
Velocity	1.5m/s
Inner Radius:	.015m
Outer Radius	.017m
Specific Heat	4200J/kgK
Density	1000kg/m3
Conductivity	.6W/mK
Reynolds	159.6U
Prandt	1.9646U
Nusselt	7.483U
Convection Co-eff	149.66W/m2K
Pressure drop	451kPa
Pump Power	.1MW
required thickness	.00167m



Heat Removal II

Attenuation and Coolant Channels
Kumar Singh

Overview

1) First wall: 10 mm of Beryllium, 22 mm Cu, followed by 18mm ODS Steel
2) Coolant Channel: 0.5 m total
    a) 1 coolant layer
    b) ~5% ODS Steel Structure, ~5% SiC insulator, ~90% Pb17Li coolant
3) Carbide neutron reflector: 20mm
    a) assumed albedo of 60%
4) Shield: 1m thick
    a) 50% SS 50% B_4C

Attenuation

- Heat flux is directly related to neutron flux past the FW
- Neutrons are attenuated while traversing past the FW
- Attenuation can be related to macroscopic cross section
    - Absorption and Scattering cross sections taken from NIST
- Neutron flux drops off exponentially as a function of distance from the first wall

$$\varphi(x) = \varphi_o e^{-\mu x}$$

Heat Distribution

- Heat distribution follows same trend
- 1.88 MW/m^2 into the FW
    - Temperature rise of 75 degrees in 10mm Be
    - Temperature rise of 100 degrees in 22mm Cu
    - Temperature rise of 1300 degrees in 18mm ODS Steel

- Attenuated to 1.82 MW/m^2 before entering coolant
    - 0.60 MW/m^2 leaves coolant (60% is reflected)
        - Carbide reflector chosen due to high scattering cross section
        - Would lose 360 kW/m^2 without it
    - total of 1.6 MW/m^2 deposited in coolant

Heat Distribution

- 0.24 MW/m^2 incident on the shield
  - 50% SS, 50% B_4C
- Need to attenuate four orders of magnitude to ensure magnet safety
- Boron Carbide has a high absorption cross section
  - 26 W/m^2 leaving the shield
  - Very low, could be used to power electronics

Tolerances

Material	Limit	Actual
Be (FW)*	20 MW/m^2	1.88 MW/m^2
Copper (FW)*	30 MW/m^2	1.88 MW/m^2
SS (FW)*	2 MW/m^2	1.85 MW/m^2
Tungsten (Divertor)	8 MW/m^2	1.78 MW/m^2

*There may be some concern about the decrease of thermal conductivity as a function of wall loading and temperature. However, no significant change will occur and the above materials will remain within safe operating limits.

Coolant Channel

- Needs to remove 1.6 MW/m^2 of heat
- $Q=mC(T-T_i)$
  - Chosen Temperature change of 200 degrees
  - C = 190 J/kg K
- Mass flow needed is approx. 19,000 kg/s, total flow rate of 8 m/s
  - 50 coolant tubes
  - Velocity in each tube needs to be 0.16 m/s

Pumping Power

- Reynolds number ~ 4 x 10^6 (highly turbulent)
- Friction factor of ~0.012
- Frictional pressure drop ~4000 Pa/m or 0.15 MPa
- MHD Pressure Drop ~0.33 MPa without SiC insulation
  - becomes negligible due to insulation properties
- Pumping power
  - 0.15 MPa needs to be pumped against
  - With 60% pumping efficiency, power needed ~1 MW/tube (50 MW total or 5% of total power)
  - With 40% pumping efficiency, power needed ~1.5 MW/tube (75 MW total 7.5% of total power)

Summary

- Tungsten Divertor
    - water @ 1.5 m/s in 180 tubes of 17mm radius
- Coolant channels
    - Lithium-lead @ 0.16 m/s in 50 tubes of 0.20 m^2 flow area
- Carbide reflector
    - reflects ~20% of thermal power into coolant
- Boron Carbide shield
    - absorbs remaining heat
- Cooling pumping power 5% - 7.5% of thermal output

References

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