Geometry and Thermal Hydraulics: Self-Cooled LiPb Blanket in SiC Structure for ARIES-AT Power Plant

Outboard Blanket Presented

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Subjects Covered

- **Design philosophy and restrictions**
- **Overall blanket design**
- **First wall design and configuration**
- **Blanket design**
- **Thermal hydraulics**
- **Preliminary stress estimates**
- **Maximum SiC temperature**
- **Power cycle efficiency**

Design Philosophy and Parameter Restrictions

The three main guiding principles in the design of this blanket, in the order of importance, are

1) Maximizing safety

2) Maximizing thermal efficiency

3) Achieving flexibility

These aspects to be achieved while maintaining SiC properties at:

•Maximum thermal conductivity	20 W/mK
•Maximum allowable operating temperature	1000 C
•Maximum allowable primary stress	140 MPa
•Maximum allowable secondary stress	190 MPa

A goal of the design is to limit the LiPb/SiC interface temperature to 900 C and if possible to 800 C.

Safety Considerations

The main safety considerations are:

- **Compatible materials: No chemical or thermal reactions to produce high pressure or release large amounts of energy**
- **Low pressure: The maximum pressure in the FW is 0.75 MPa of which 0.5 MPa is hydrostatic. The typical household water pressure is 0.6 MPa.**
- **Low afterheat: The first wall and blanket cells are designed to drain out by gravity, thus leaving only the SiC structure, which has low afterheat.**

Maximizing Power Cycle Efficiency

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Two design options are pursued:

1) Conservative design

- **Outlet LiPb temperature 1000 C**
- **Power cycle efficiency 55%**

2) Aggressive design

- **Outlet LiPb temperature 1100 C**
- **Power cycle efficiency 59–60%**

Achieving Design Flexibility

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- **Design flexibility is achieved by making the FW, blanket and shield components physically separate and independent of each other.**

- **Each of these components can be separated from the blanket complex by cutting one supply tube and one return tube.**

- **The FW and near first wall Cell #1 blanket component can be replaced separately while allowing the longer life components to remain undisturbed.**

Overall Blanket Configuration

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• **The FW and blanket are divided into four separate units**

1) First wall
2) Blanket cell #1
3) Blanket cell #2
4) Shield

• **The LiPb coolant goes through the FW, entering on the bottom and exiting at the top.**

• **At the top the coolant collects into a manifold which has three tubes leading from it, one each feeding cell #1, cell #2 and the shield.**

• **In cell #1, cell #2 and the shield, the coolant goes through channels in the walls of the cell before entering the cell proper at the top.**

• **The coolant then flows down through the cell proper and exits on the bottom.**

• **Small holes in the wall channels on the bottom drain the LiPb from the channels when the blanket needs to be drained.**

Outboard Blanket/Shield Schematic and Coolant Flow Direction

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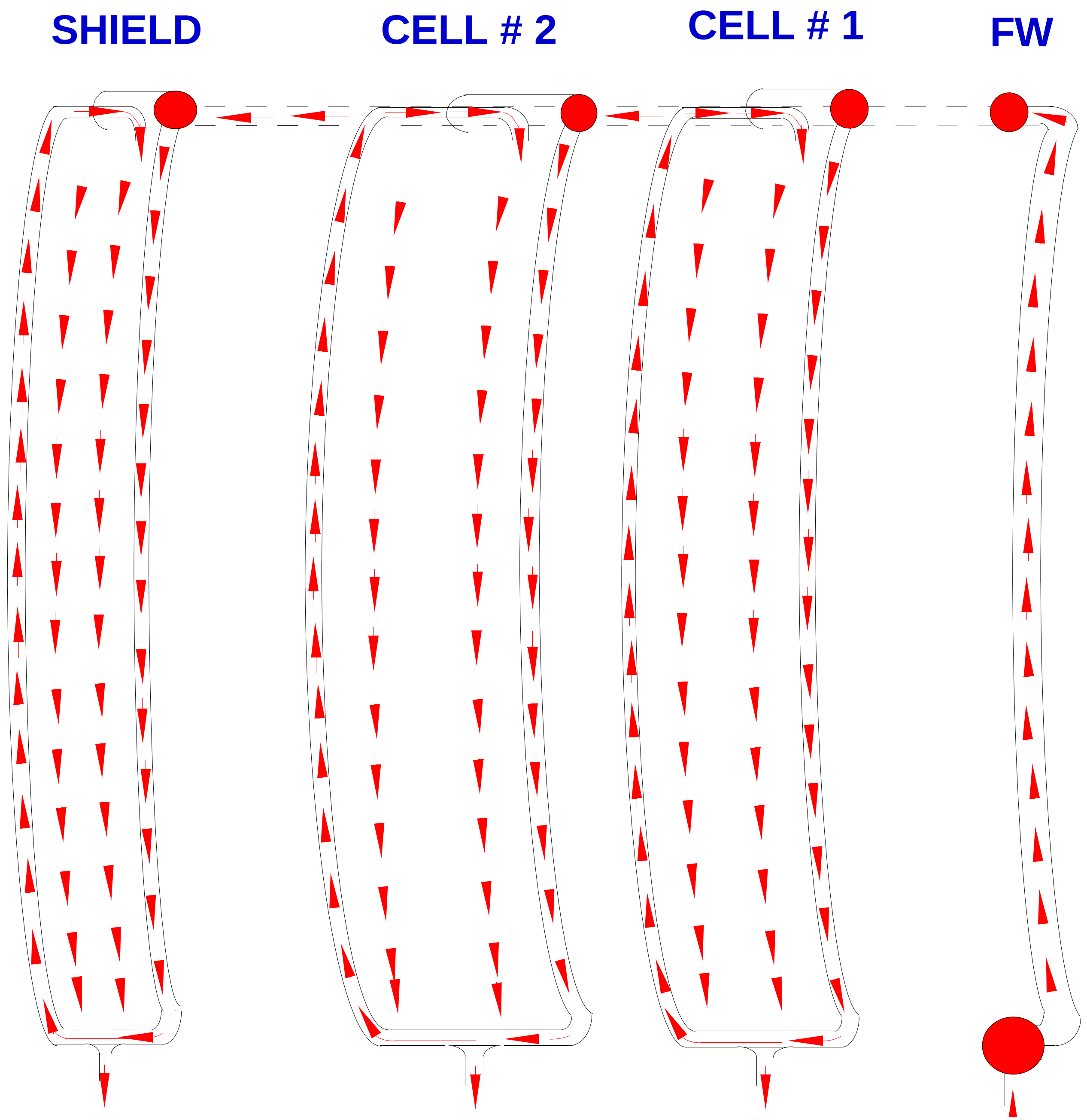


First Wall Design

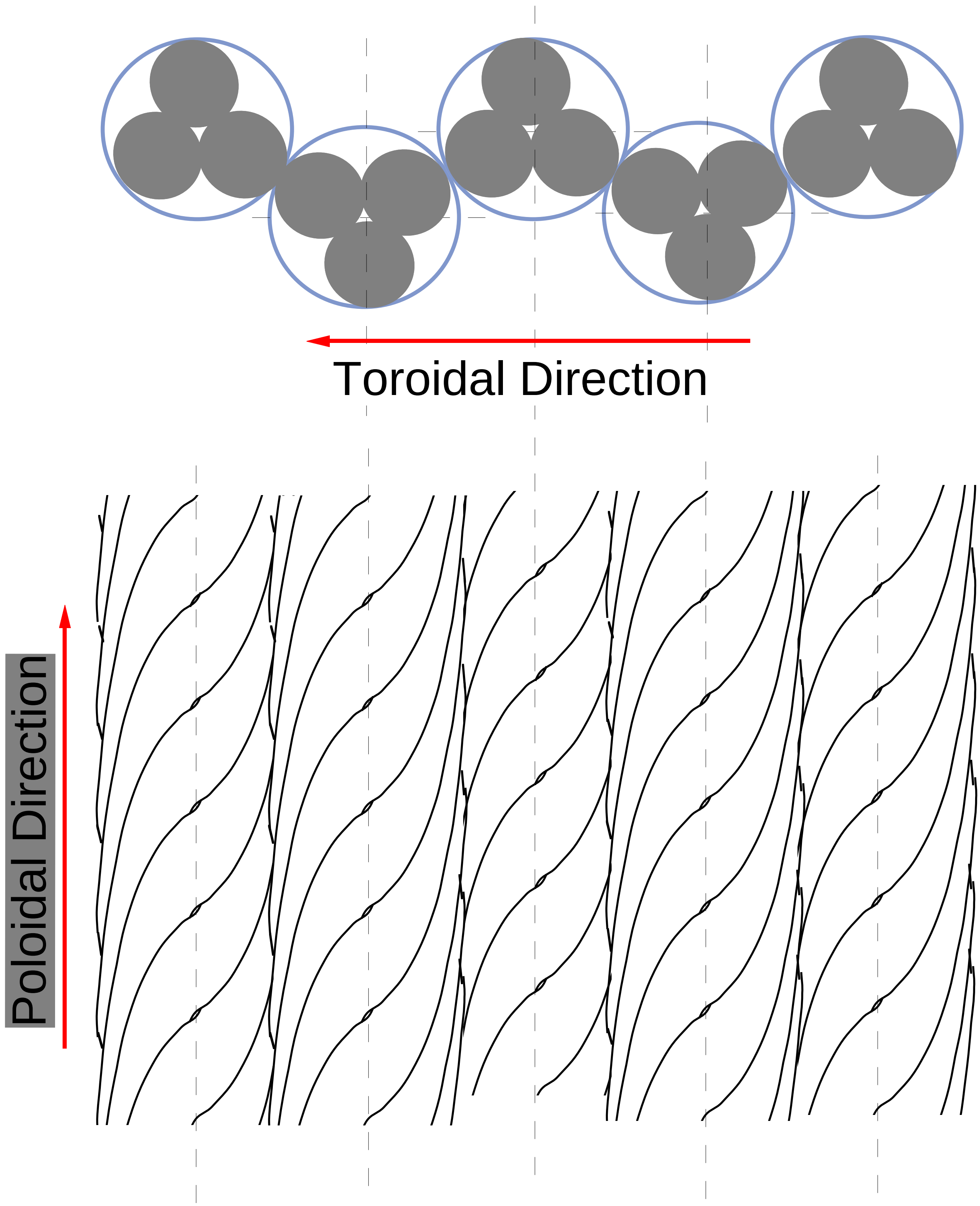
- **The first wall consists of bundles made up of three SiC spirally twisted tubes extending poloidally from the bottom to the top of the blanket and cooled with LiPb.**

- **At the midplane the bundles are placed in a configuration which insures no shine-through of surface heating from the plasma.**

- **At the top and bottom, the same number of bundles are spread out radially but compressed toroidally to allow for the decrease of toroidal extent due to the smaller major radius.**

- **The tubes are made of SiC/SiC composite material, are 3 cm in internal diameter, have a wall thickness of 0.3 cm and on the side facing the plasma, are coated with 0.2 cm of CVD SiC armor.**

- **For the OB blanket the total number of bundles is 512 and the total number of tubes is 1536.**



First Wall Bundle Arrangement

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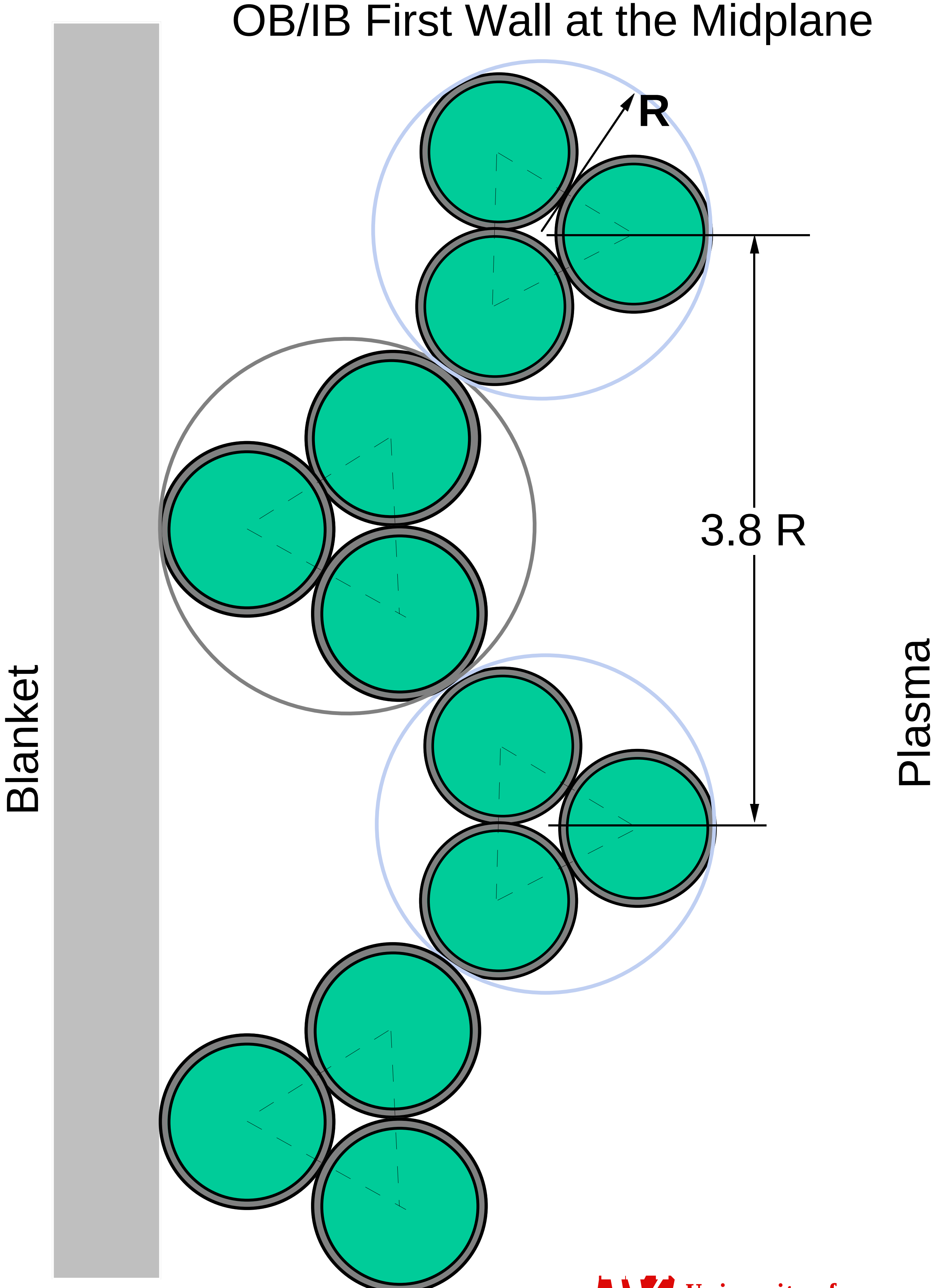
OB/IB First Wall at the Midplane



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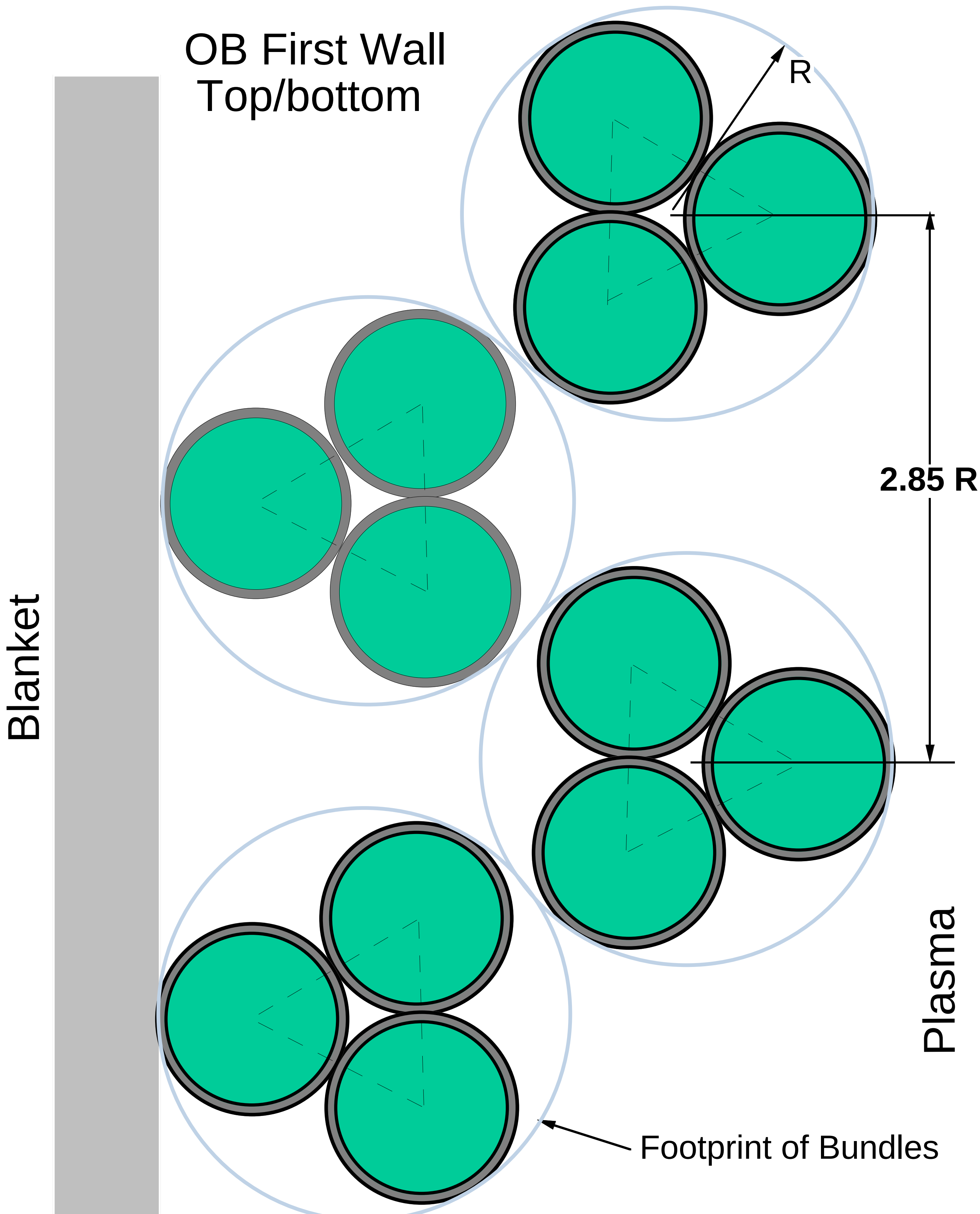

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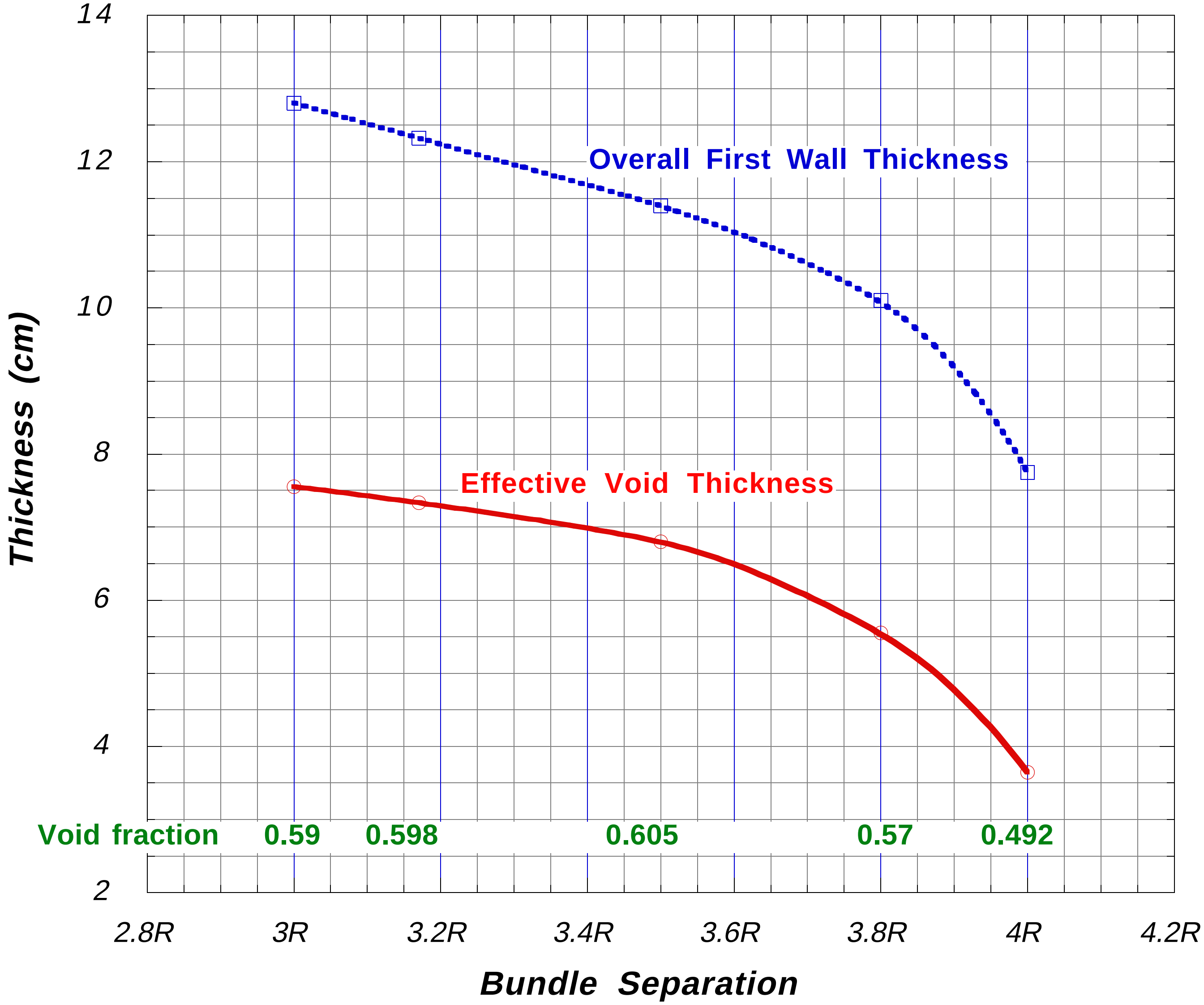
Effective Void Thickness at Mid-Plane First Wall as a Function of Bundle Separation



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First Wall Thermal Hydraulics

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• **Nuclear Heating in the FW**		**385 MW**
Front SiC wall	**53 MW**	
LiPb	**317 MW**	
Rear SiC wall	**15 MW**	
Max. Surface Heating	**0.7 MW/m^2**	
Total OB surface heating		**147 MW**
Total heating in FW		**532 MW**

• **LiPb supply temperature to FW (C)**	**600**
LiPb exit temperature from FW (C)	**760**
Mass flow rate (kg/s)	**17,848**
Velocity in tubes (m/s)	**1.86**
Max. SiC/SiC temperature (C)	**916**
Max. CVD SiC temperature (C)	**1008**
Max. LiPb/SiC interface temperature (C)	**803**

First Wall Parameter List

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Nuclear heating in FW (MW)	**385**
Surface heating on FW (MW)	**147**
Peak specific heating in FW SiC (W/cm^3)	**31**
Avg. specific heating in FW SiC (W/cm^3)	**26**
Mass flow rate in FW (kg/s)	**17848**
Inlet LiPb temperature (C)	**600**
Outlet LiPb temperature (C)	**760**
Coolant velocity (m/s)	**1.86**
Re	**$6.067 x 10^6$**
Pr	**$7.3 x 10^{-3}$**
Nu	**27.68**
Heat transfer coefficient (W/m^2K)	**19118**
T_{max} SiC/SiC (C)	**916**
T_{max} CVD SiC (C)	**1008**
T_{max} LiPb/SiC interface (C)	**803**
Avg. LiPb density (kg/m^3)	**8846.6**
Avg. LiPb Cp (J/kgK)	**186.3**
Avg. LiPb thermal conductivity (W/mK)	**20.72**
Primary SiC stress (MPa)	**75**
Secondary SiC stress (MPa)	**113**

Coolant Flow Direction in Cell # 1, Cell # 2 and Shield

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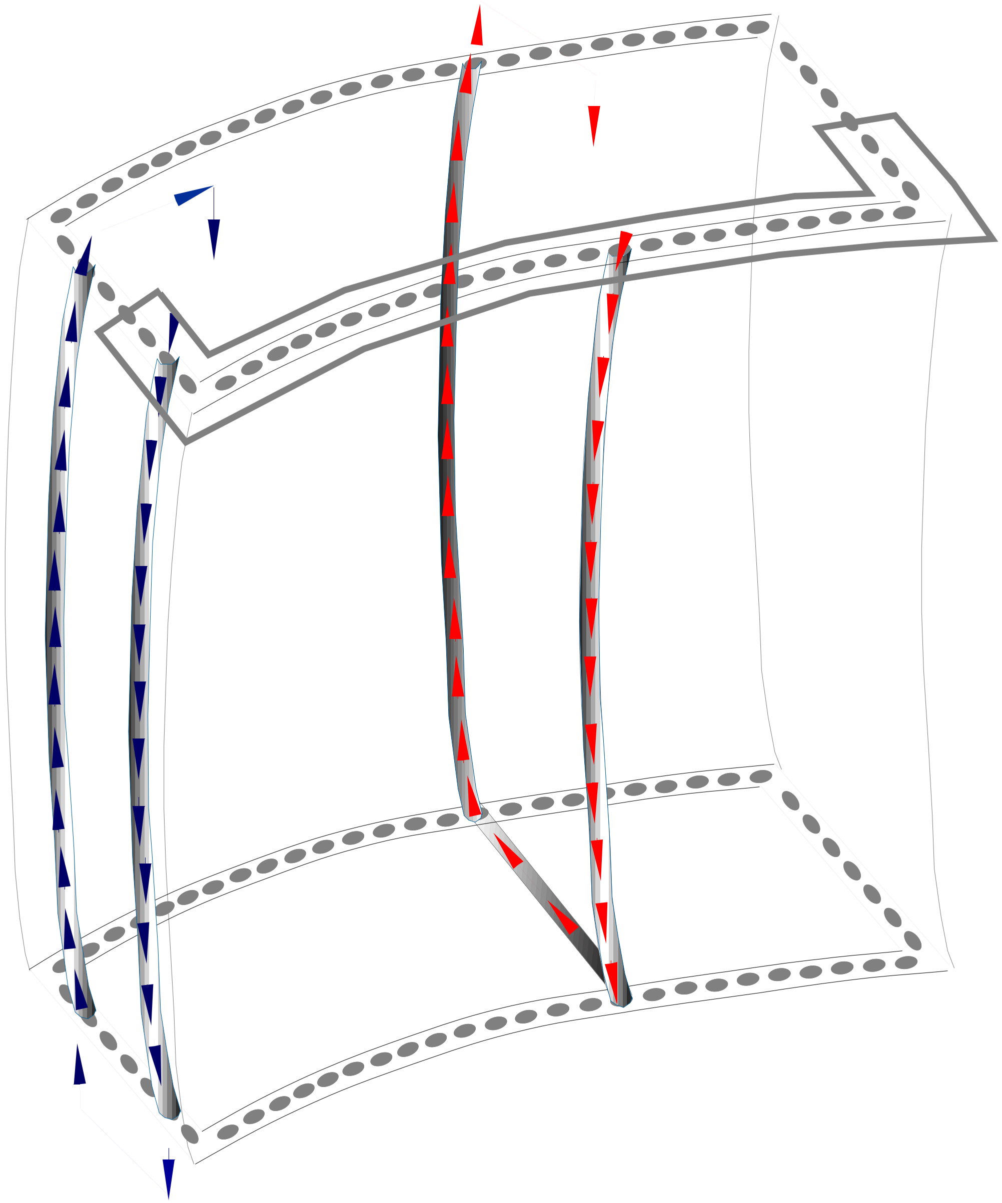

Outboard Blanket/Shield Schematic with Thermal Hydraulics Parameters

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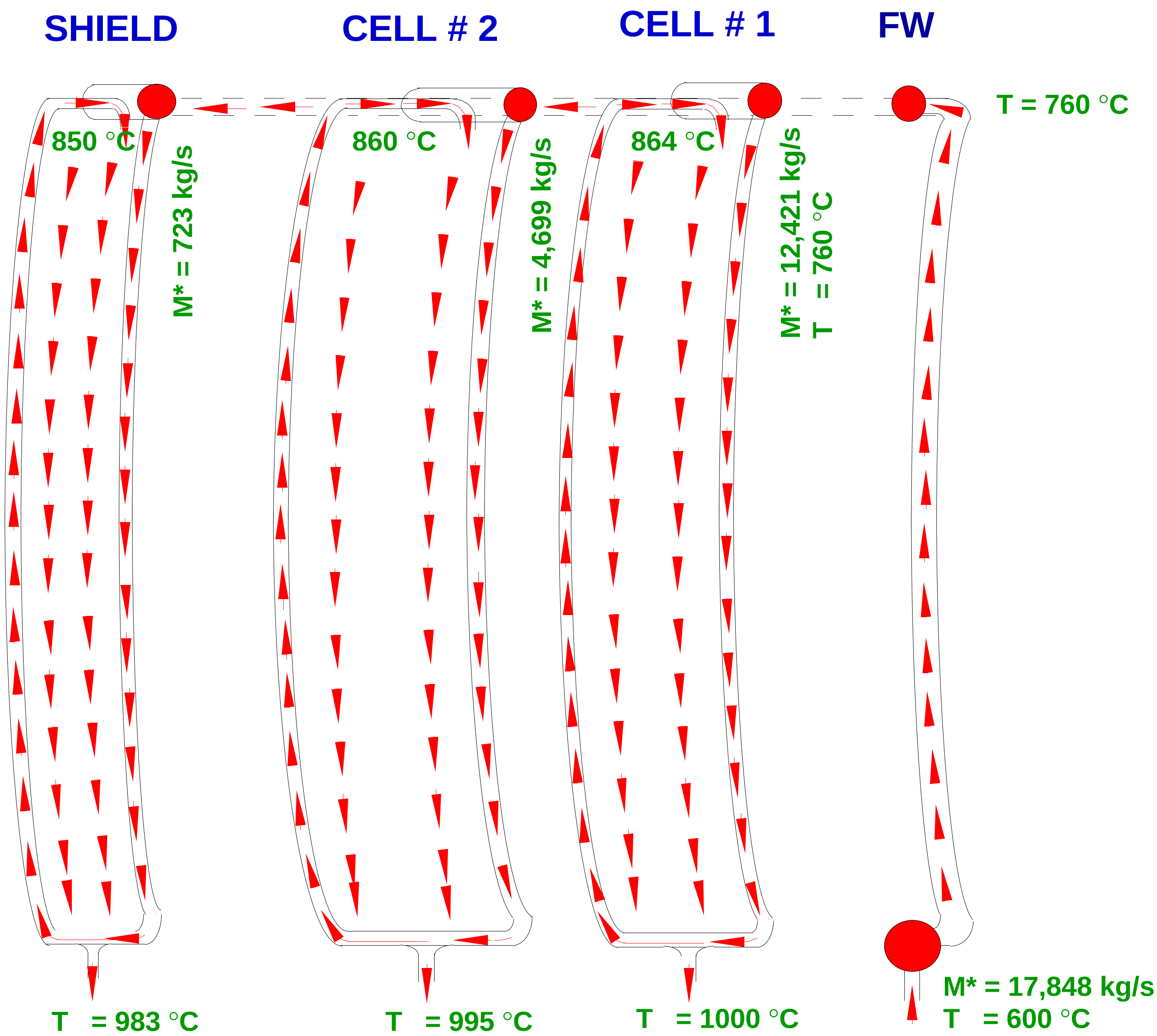

Temperature distribution in cell #1 walls

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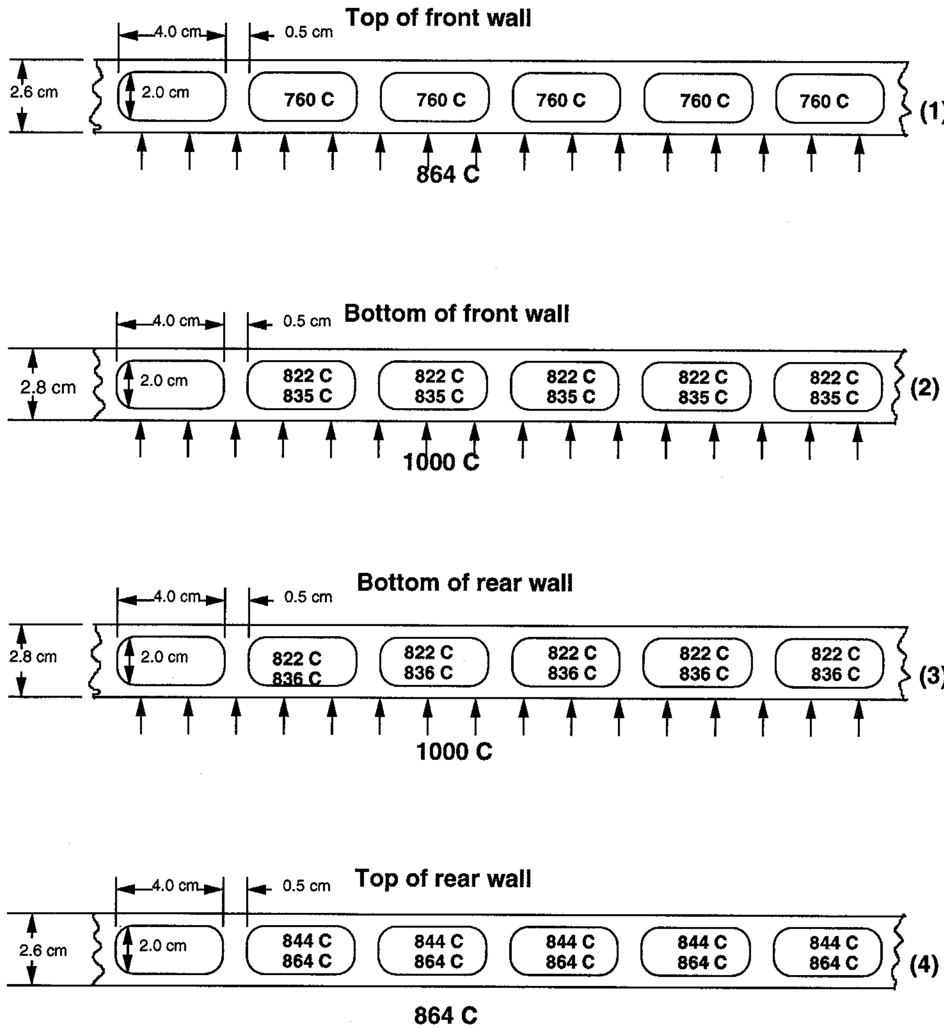

Upper temperature calculated without heat transfer from cell proper
Lower temperature calculated with heat transfer from cell proper

Cell #1 Thermal Hydraulics

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• **Total nuclear heating in Cell #1 (MW)**		**550**
Nuclear heating in front wall (MW)	**128**	
Nuclear heating in rear wall (MW)	**37**	
Nuclear heating in side walls (MW)	**25**	
Nuclear heating in top & bottom (MW)	**4**	
Nuclear heating in cell proper (MW)	**356**	
• **Energy conducted from cell to walls (MW)**	**50**	
Resultant heating in walls (MW)	**194+50=**	**244**
Resultant heating in cell proper (MW)	**356−50=**	**306**
		550
• **LiPb supply temp. to cell walls (C)**	**760**	
LiPb exit temp. from cell walls (C)	**864**	
Mass flow rate (kg/s)	**12,421**	
Velocity in channels (m/s)	**2.19**	
• **LiPb entry temp. into cell proper (C)**	**864**	
LiPb exit temp. from cell proper (C)	**1000**	
Velocity in cell proper (m/s)	**0.21**	
Max. SiC/SiC temperature (C)	**895**	
Max. SiC/LiPb interface temp. (C)	**895**	

Cell #1 Parameter List - 1

•Cell Wall Parameters

Nuclear heating in cell walls (MW)	194
Heat conducted from cell to walls (MW)	50
Resultant heat in cell walls (MW)	244
Resultant heat in cell proper (MW)	306
Total heating in cell (MW)	550
Mass flow rate in walls and cell (kg/s)	12,421
LiPb supply temp. to cell walls (C)	760
LiPb exit temp. from cell walls (C)	864
Channel dimensions in cell walls (cm x cm)	2 x 4
Equivalent diameter of channel (cm)	2.67
Velocity in channels (m/s)	2.19
Re	7.35×10^{5}
Pr	5.50×10^{-3}
Nu	26.2
Heat transfer coefficient (W/m^2K)	22,707
Avg. ρ in cell walls (kg/m^3)	8639
Avg. C_p in cell walls (J/gK)	185.2
Avg. μ in cell walls (Pa s)	6.87×10^{-4}
Avg. k in cell walls (W/mK)	23.14

Cell #1 Parameter List - 2

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•Cell Proper Parameters

Heat in cell proper (MW)	306
Inlet LiPb temp. into cell proper (C)	864
Outlet LiPb temp. from cell proper (C)	1000
Mass flow rate (kg/s)	12,421
Flow area in cell proper (m^2)	7.0
Velocity in cell proper (m/s)	0.21
Re	5.92×10^5
Pr	4.29×10^{-3}
Nu	20.24
Heat transfer coefficient (W/m^2K)	2346
Avg. ρ in cell proper (kg/m^3)	8424
Avg. C_p in cell proper (J/gK)	184.02
Avg. μ in cell proper (Pa s)	5.98×10^{-4}
Avg. k in cell proper (W/mK)	25.7
Max. temp. of SiC/SiC (C)	895
Max. SiC/LiPb interface temp. (C)	895

Pressure Drop and Pumping Power

- **In First Wall**

$$\mathbf{Re} = 6.07 \times 10^5 \quad f = 0.135, \; L = 6 \text{ m}, \; v = 1.86 \text{ m/s}, \; \rho = 8843 \text{ kg/m}^3$$

$$\Delta P = 0.42 \text{ MPa}$$

- **In Cell Walls**

$$\mathbf{Re} = 7.35 \times 10^5 \quad f = 0.013, \; L = 12.5 \text{ m}, \; v = 2.18 \text{ m/s}, \; \rho = 8639 \text{ kg/m}^3$$

$$\Delta P = 0.12 \text{ MPa}$$

- **Total** $\Delta P = 0.162$ **MPa**
  Use a factor of 1.5 for manifolds. $\Delta P = 0.243$ **MPa**

- **Pumping power** $= \dot{V}\Delta P = \frac{\dot{M}}{\rho}\Delta P$
  $= 0.50$ **MW**

Preliminary Stress Estimates - 1

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First Wall Tubes

Pressure on bottom of FW tubes is:

$$P = 0.243 + 0.5 = 0.743 \text{ MPa where } 0.5 \text{ MPa is hydrostatic}$$

- **Primary stress is:** $\sigma_p = \frac{Pr}{t}$, $r_{\text{avg}} = 1.65$ cm t = 0.3 cm

$$\sigma_p = 4.1 \text{ MPa}$$

- **Secondary stress** $\sigma_s \pm \frac{\alpha}{2}\frac{E}{k(1-\nu)}\left(W_s t + \frac{W_n}{2} t^2\right)$

$\alpha = 4.4x10^{-6}$, $E = 360$ GPa, $k = 20$ W/mK, $\nu = 0.167$, $W_s = 0.7$ MW/m^2, $W_n = 31$ W/cm^3, $t = 0.3$ cm

$$\sigma_s = 113 \text{ MPa}$$

Max. σ_p occurs on the bottom of the tubes where P is the highest.

Max. σ_s occurs at tube's midplane where W_s and W_r peak.

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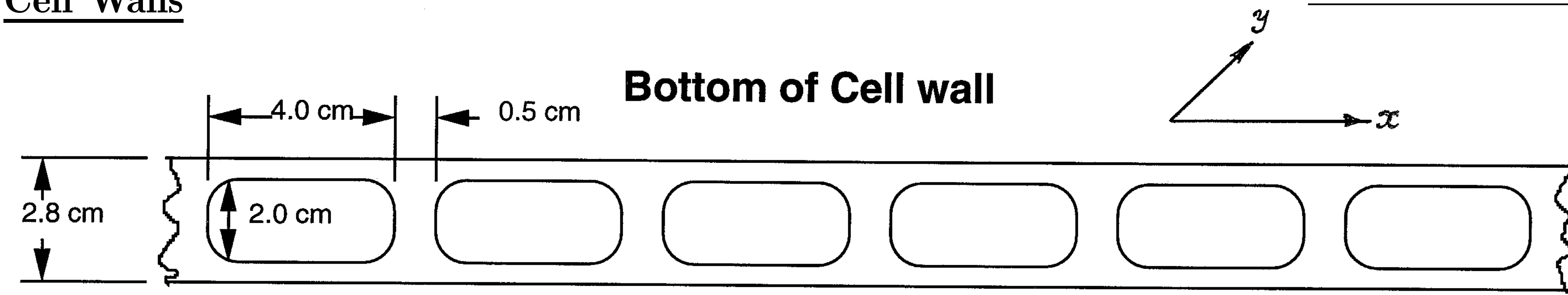
Cell Walls



Calculating the flexural rigidity of the plate:

$$^{*}D_x = 418.6 \text{ GPa cm}^3, D_y = 445.2 \text{ GPa cm}^3$$

From $D = \frac{Eh^3}{12(1-\nu^2)}$, **calculate equivalent solid thickness:**

$$h_x = 2.387 \text{ cm} \qquad h_y = 2.436 \text{ cm}$$

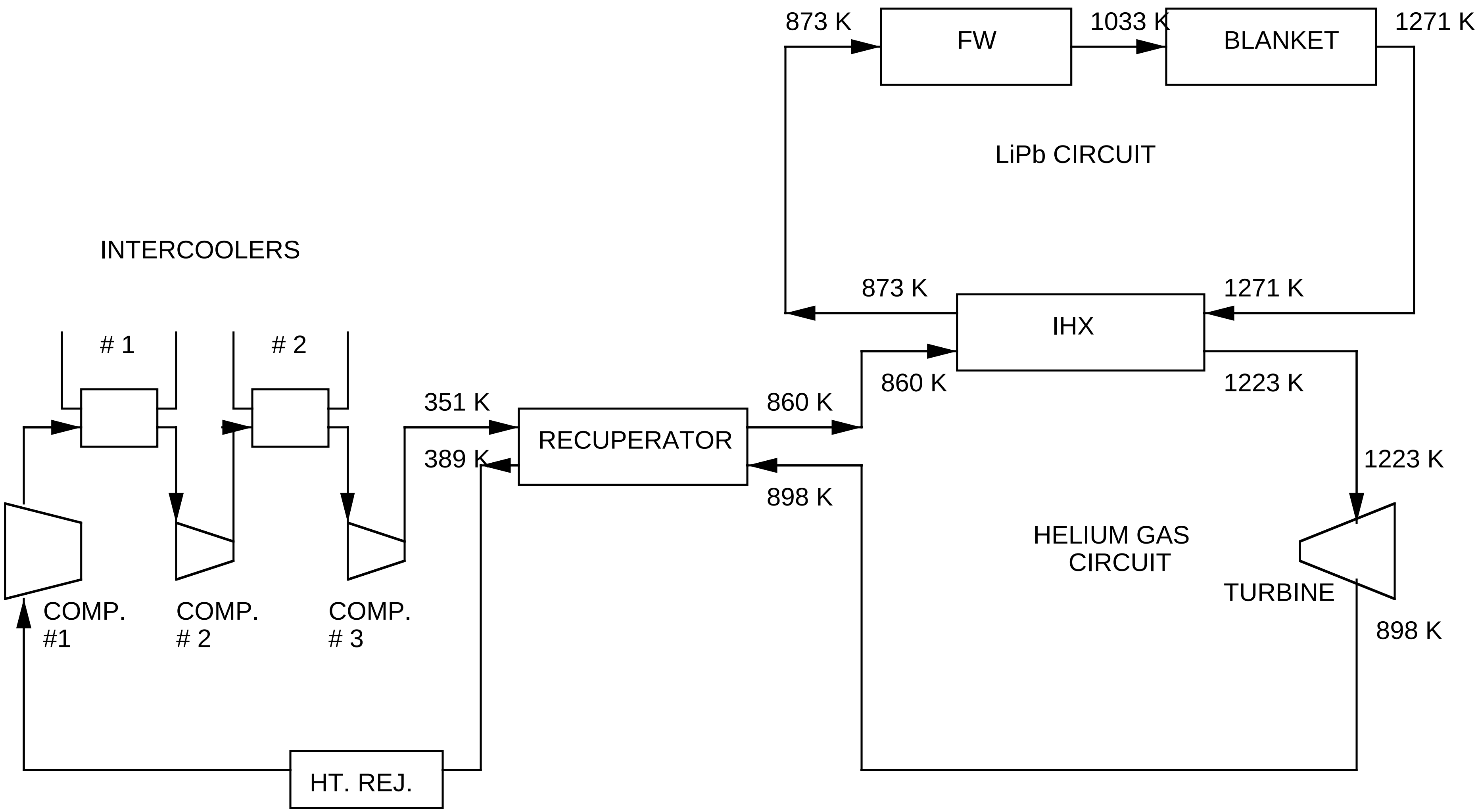
Hydrostatic pressure on cell wall is 0 MPa on top, 0.5 MPa on bottom.

****Using coefficients for a hydrostatically loaded rectangular plate with three sides built in and a fourth side free:**

$$\sigma_x = 124.7 \text{ MPa}, \qquad \sigma_y = 107.5 \text{ MPa}$$

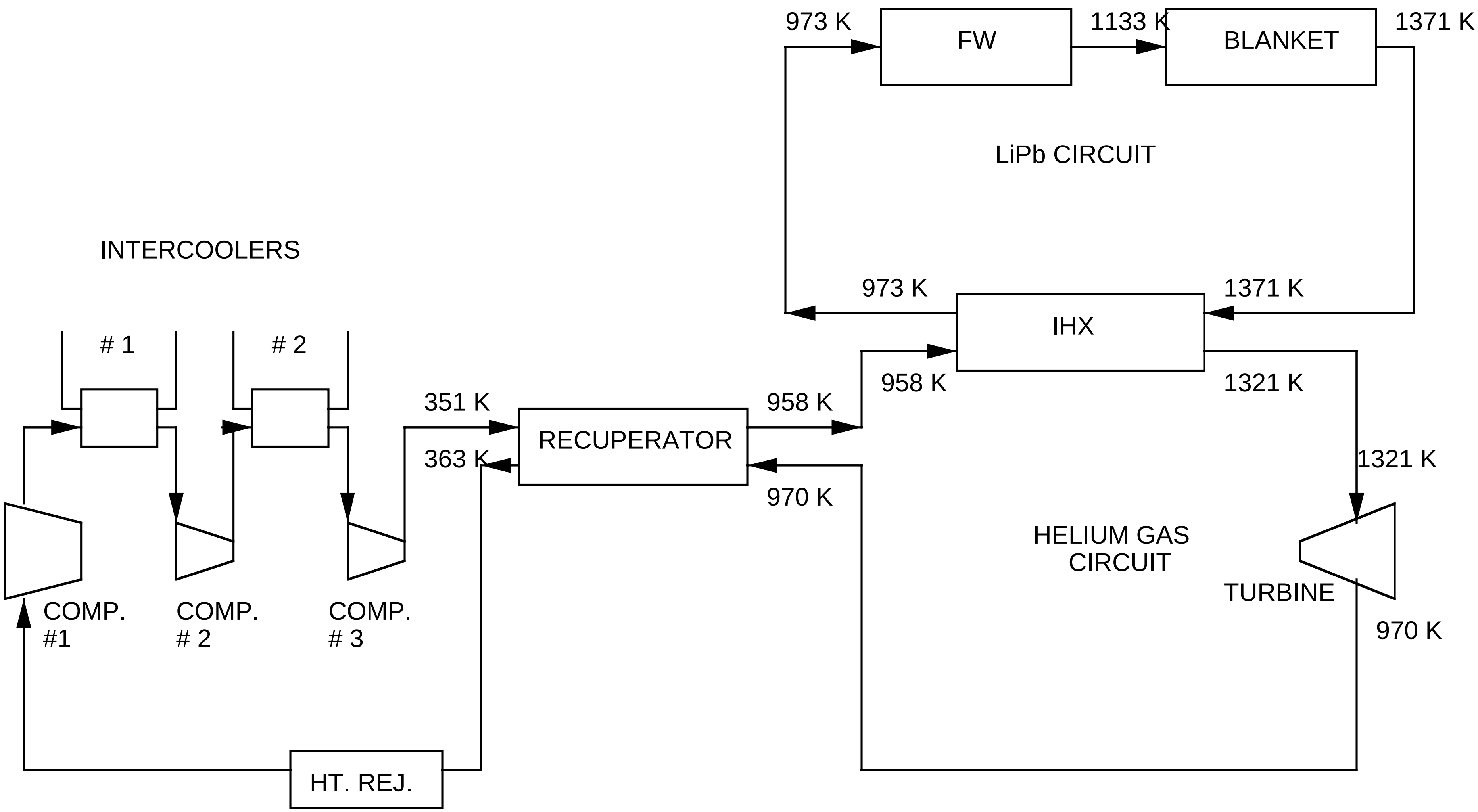
"Theory of Plates and Shells", S. Timoshenko and Woinovsky-Krieger, second edition, *pp. 368–369 and **pp. 216.

Circuit diagram for self-cooled LiPb blanket-Conservative option



Estimated Efficiency 55.8%

Circuit diagram for self-cooled LiPb blanket-Aggressive option



Estimated Efficiency 58.8%

Power cycle efficiency using the Brayton Cycle

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Conservative Design Option:

LiPb outlet temperature	1000 C
T max SiC/SiC	916 C
T max SiC/LiPb	895 C
Power cycle efficiency	55.8 %

Aggressive Design Option :

LiPb outlet temperature	1098 C
T max SiC/SiC	1016 C
T Max SiC/LiPb	996 C
Power cycle efficiency	58.8 %

Options to consider for improving blanket performance

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- In the self-cooled LiPb blanket, the cooling of the FW, blanket and shield are closely connected. Thus, anything done to the FW cooling affects the blanket and vice-versa.

- The main object is to increase the LiPb outlet temperature while maintaining T max of SiC/SiC at or near 1000 C

At the first wall:

  - Increasing the velocity to enhance the Nusselt number. There is a limit of how much this will help and will cost pumping power.

In the blanket:

  - Using a low thermal conductivity SiC for insulating the lower cell wall parts can help increase the LiPb outlet temperature while maintaining T max of the SiC at or near 1000 C

Summary and Conclusions

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- A self-cooled LiPb blanket for ARIES-AT has been designed which embodies good safety features and uses compatible materials with low afterheat.

- An innovative first wall consisting of bundles of three spiraling SiC tubes has been designed which takes advantage of centrifugal forces to enhance heat transfer and even out temperatures.

- A single coolant at very low pressure means that leaks into the plasma chamber are not likely to occur while pumping power is very low.

- Flexibility has been provided by separating the FW from the blanket and shield, making it possible to replace any of these components by simply disconnecting a supply and a return tube.

- A very attractive thermal cycle efficiency ranging from 56-59 % can be achieved while maintaining structural SiC at or near 1000 C