ARIES-CS Power Core Options: Decision Factors and Selection for Phase II

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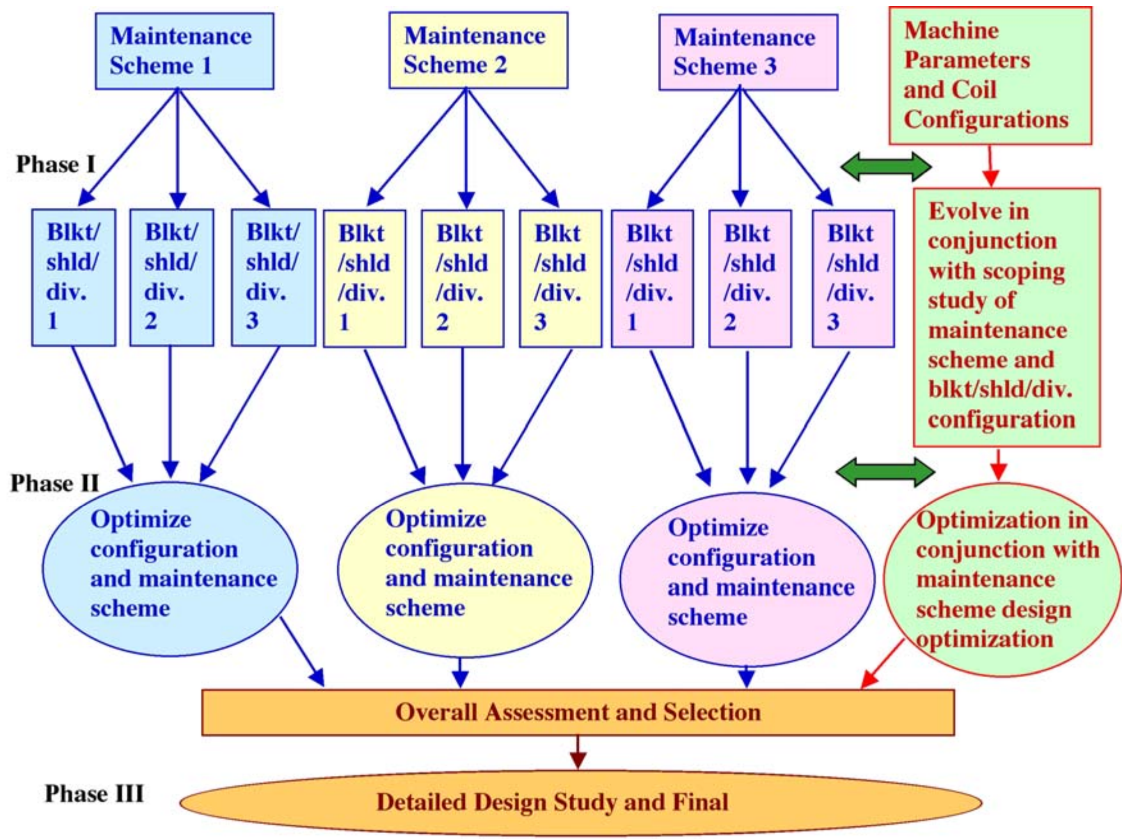
Outline

- Phase I Engineering Effort
  - Maintenance approaches
  - Blanket designs

- Down Selection for Phase II

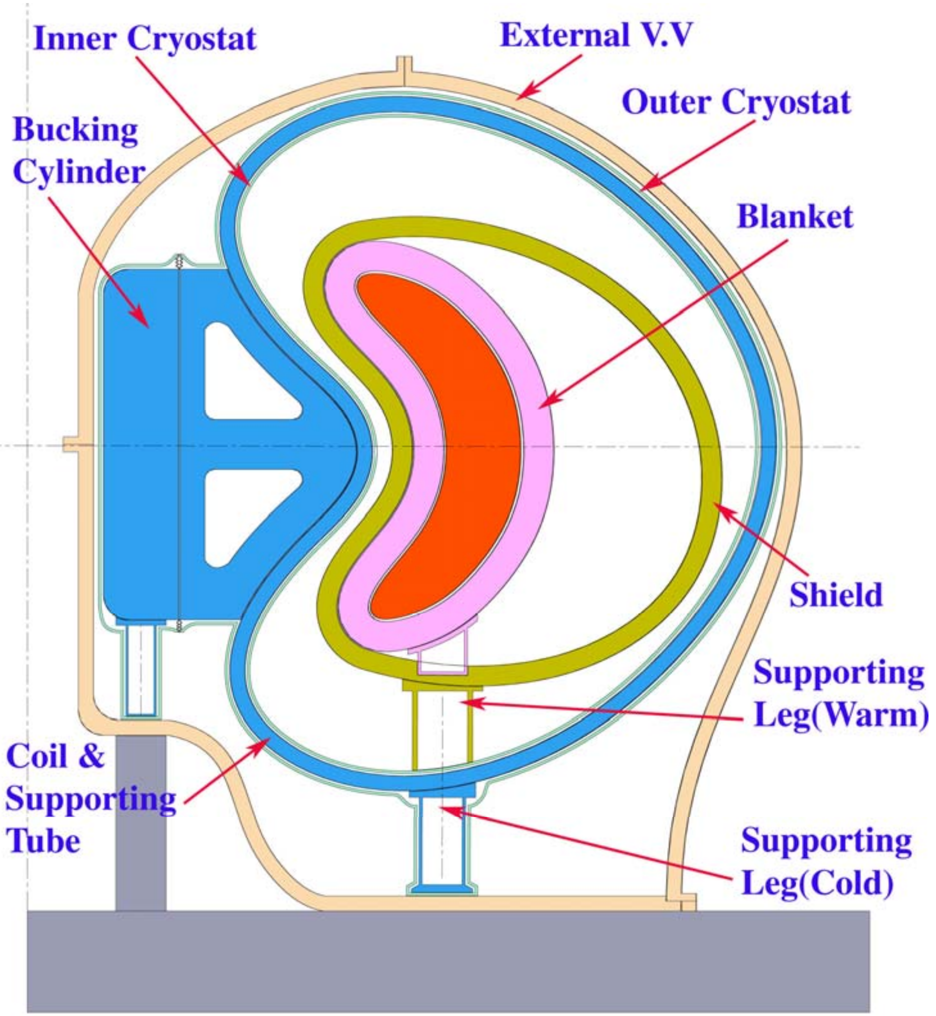
Engineering Activities During Phase I of ARIES-CS Study

- **Perform Scoping Assessment of Different Maintenance Schemes and Blanket Concepts for Down Selection to a Couple of Combinations for Phase II**
- **Three Possible Maintenance Schemes:**
  1. Field-period based replacement including disassembly of modular coil system (e.g. SPPS, ASRA-6C)
  2. Replacement of blanket modules through a few ports (using articulated boom)
  3. Replacement of blanket modules through ports arranged between each pair of adjacent modular coils (e.g. HSR)



- **Different Blanket Classes**
  1. Self-cooled Pb-17Li blanket with SiC_f/SiC as structural material
  2. Dual-Coolant blanket with He-cooled FS structure and self-cooled LM (Li or Pb-17Li)
  3. He-cooled CB blanket with FS structure
  4. Flibe blanket with advanced FS

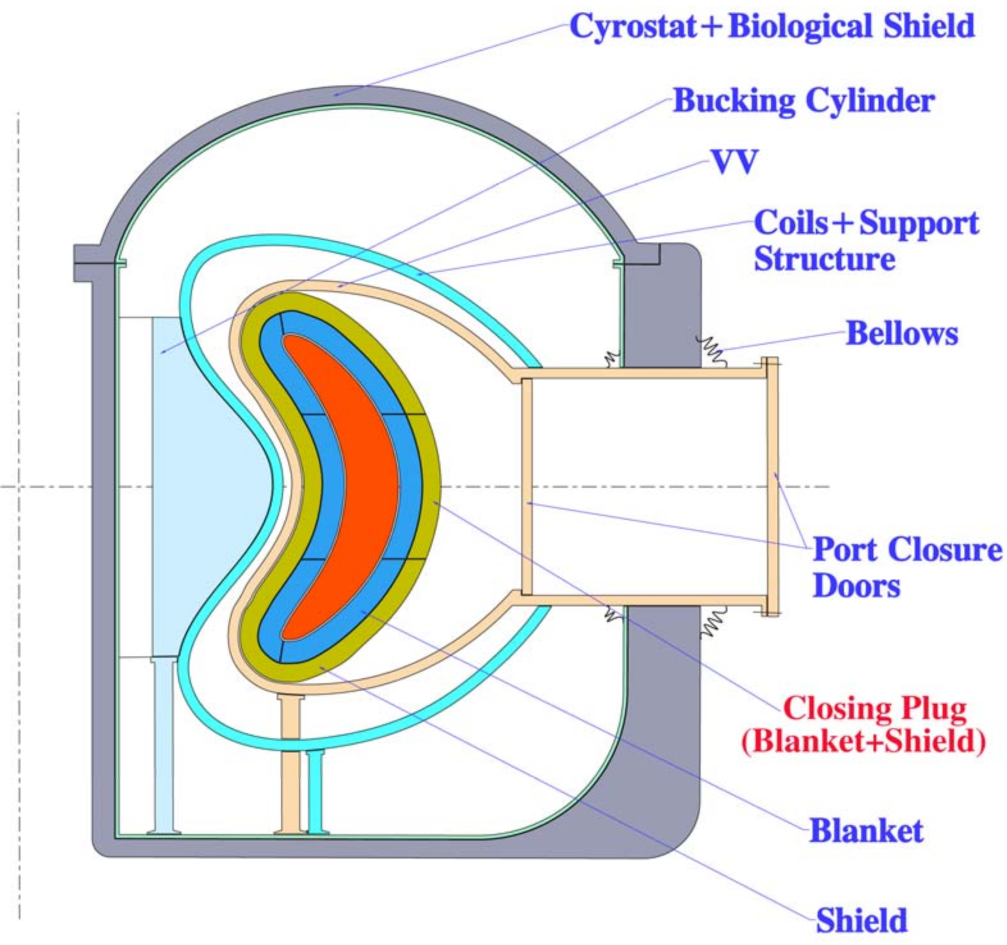
Field-Period Based Maintenance Scheme



Cross section of 3 field-period configuration at 0° illustrating the layout for field-period based maintenance.

- **The radial movement of a field period unit possible without disassembling coils in order to avoid unacceptably long down time.**
- **To facilitate opening of the coil system for maintenance, separate cryostats for the bucking cylinder in the center of the torus and for every field period are envisaged.**
- **Individual cryostats in a common external vacuum vessel**
- **Field-period maintenance provides advantage of nearly no weight limit on blanket (use of air cushions)**
- **However, better suited for 3-field period or more because of scale of field period unit movement**

Port-Based Maintenance Schemes



Cross section of 3 field-period configuration at 0° illustrating the layout for port- based maintenance.

- **Internal VV serves as an additional shield for the protection of the coils from neutron and gamma irradiation.**
- **No disassembling and re-welding of VV required for blanket maintenance.**
- **Utilize articulated boom to remove and replace blanket modules**

I. Maintenance through limited number of ports

- **Compatible with 2 or 3 field-period**
- **More restricting limit on module weight & size**

II. Maintenance through ports between each pair of adjacent coil

- **Seems only possible with 2-field period for reasonable-size reactor (space availability)**
- **"heavier" blanket module possible**

Down Selection of Maintenance Schemes for Phase II

- **It seems healthy to maintain two options:**
  1. **Field period replacement**
  2. **Replacement of relatively small modules through a small number of ports (perhaps 1 or 2 per field period) with the use of articulated booms.**
     - **More details of the procedures involved needed in both cases**
     - **Final selection of maintenance scheme will have to be compatible with the machine configuration based on our physics and system optimization during Phase II**

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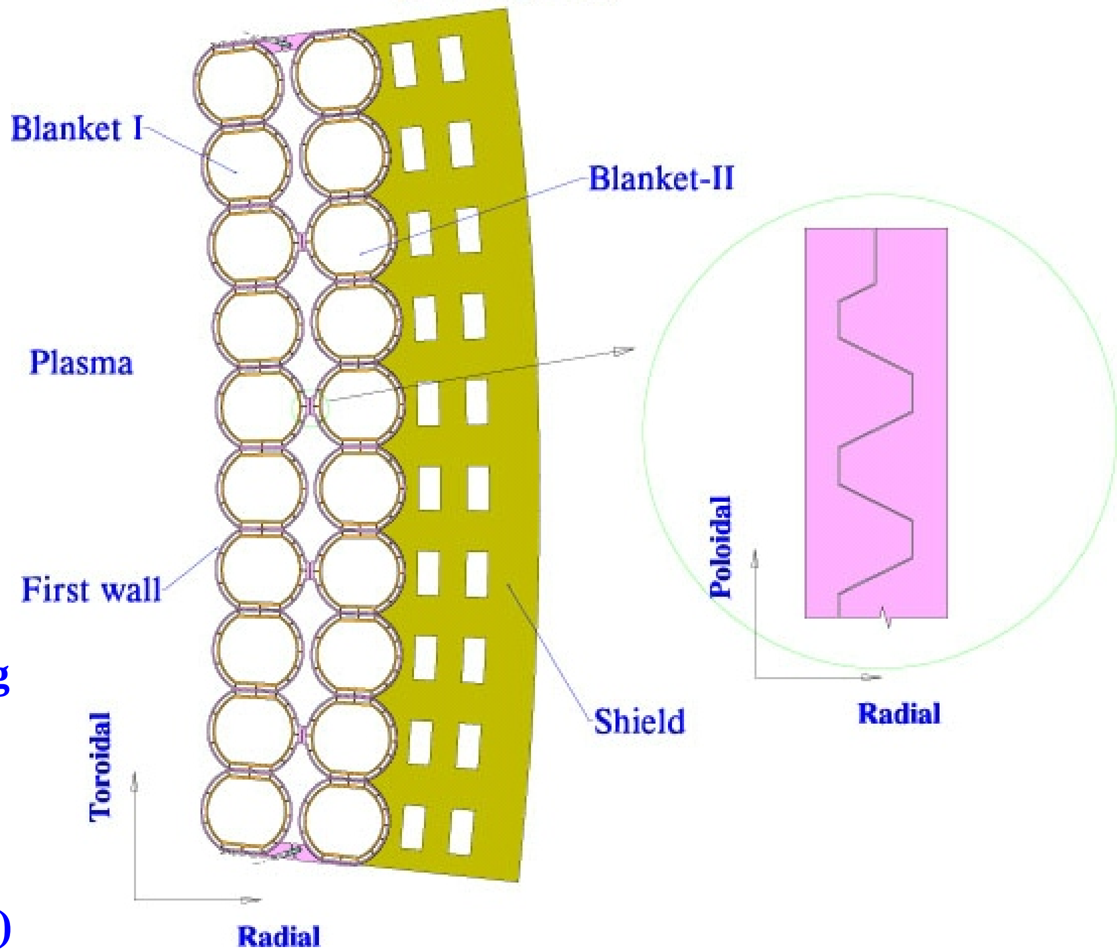
SiC_f/SiC as Structural Material and Pb-17Li as Breeder/Coolant

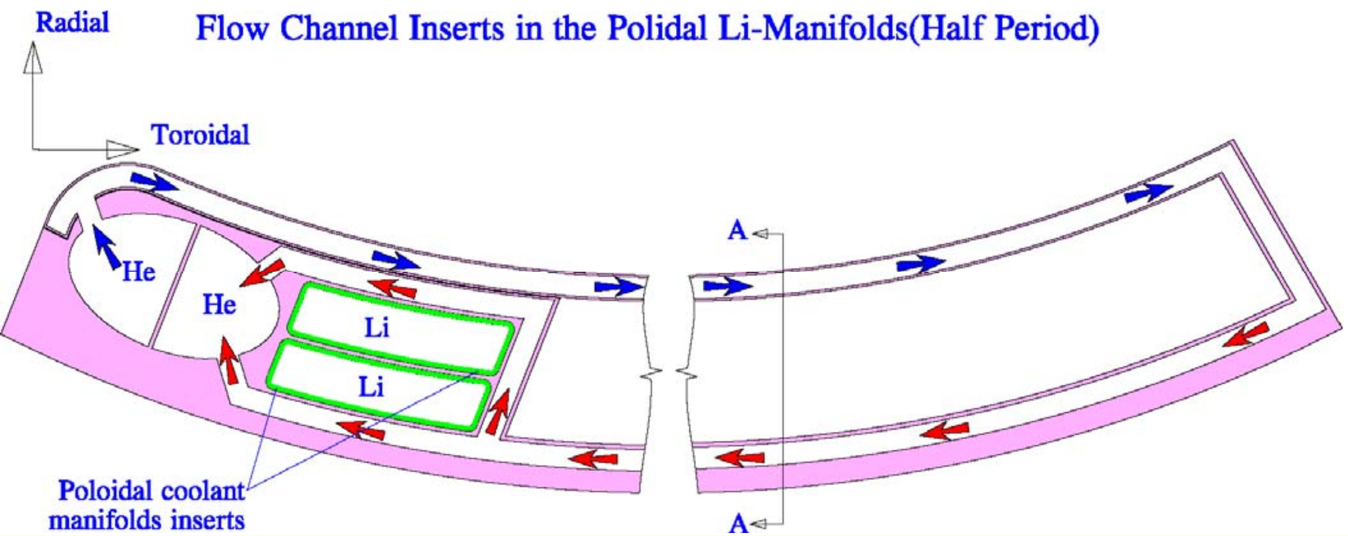
Based on ARIES-AT concept

- **High pay-off, higher development risk concept**
  - SiC_f/SiC: high temperature operation and low activation
  - Key material issues: fabrication, thermal conductivity and maximum temperature limit (including Pb-17Li compatibility)
- **Replaceable first blanket region**
- **Lifetime shield (and second blanket region in outboard)**
- **Mechanical module attachment with bolts**
  - Shear keys to take shear loads (except for top modules)
- **Example replaceable blanket module size ~2 m x 2 m x 0.25m (~ 500-600 kg when empty) consisting of a number of submodules (here 10)**
- **Thickness of breeding region for acceptable tritium breeding (~1.1 net) ~0.5 m**

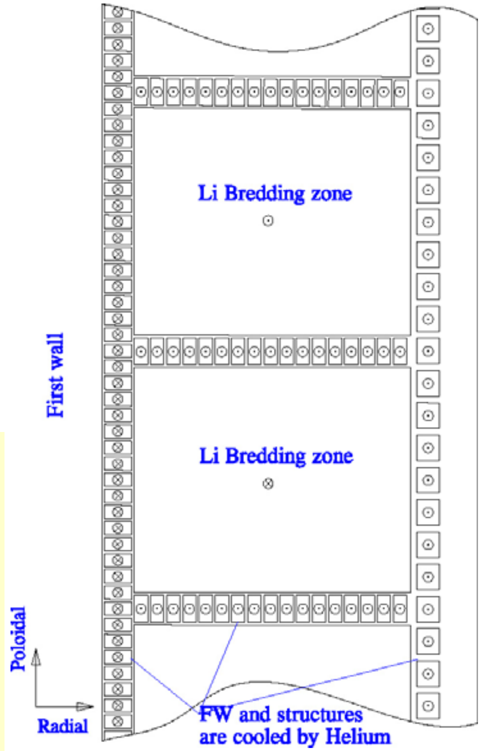
Cross Section of ARIES-CS Outboard Blanket/Shield (One Segment)



Schematic of Dual Coolant He/LM + FS Blanket Concept



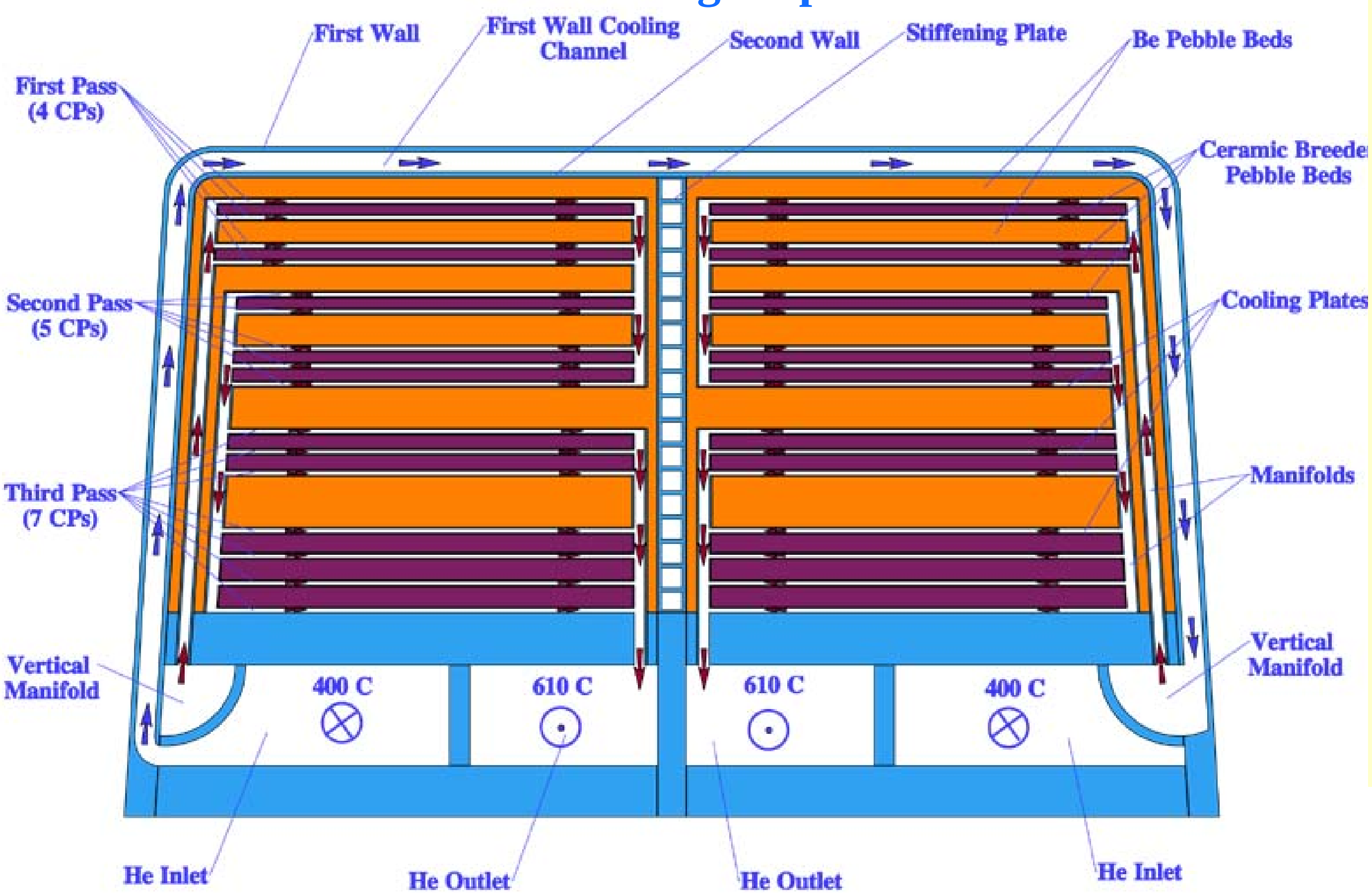
Cross section of toroidal cooling channels



- **Li and Pb-17Li as possible LM**
- **He-cooled FW (no need for FW insulator)**
- **Example shown assumes Li and field-period based maintenance (also applicable to port-based maintenance)**
- **Possibility of increasing operating temp. by local use of ODS FS**
- **Volumetric heating of the breeder/coolant provides the possibility to set the coolant outlet temperatures beyond the maximum structural temperature limits.**
  - **FW and the entire steel structure cooled with helium.**
  - **Li flowing slowly toroidally (parallel to major component of magnetic field) to minimize MHD pressure drop used as breeder/coolant in the breeding zone.**
  - **electrically insulating coating between Li and FS not required but thermal insulating layer might be needed to maintain Li/FS temp. within its limit (<~600°C)**

Ceramic Breeder Blanket Module Configuration

- Simple modular box design with coolant flowing through the FW and then through the blanket
  - 4 m (poloidally) x 1 m (toroidally) module
  - Be and CB packed bed regions aligned parallel to FW
  - Li_4SiO_4 or Li_2TiO_3 as possible CB
  - He flows through the FW cooling tubes in alternating direction and then through 3-passes in the blanket



- Initial number and thicknesses of Be and CB regions optimized for TBR=1.1 based on:
  - $T_{max,Be} < 750°C$
  - $T_{max,CB} < 950°C$
  - k_{Be}=8 W/m-K
  - k_{CB}=1.2 W/m-K
  - $\delta_{CB\ region}$ > 0.8 cm
- 6 Be regions + 10 CB regions for a total module radial thickness of 0.65 m

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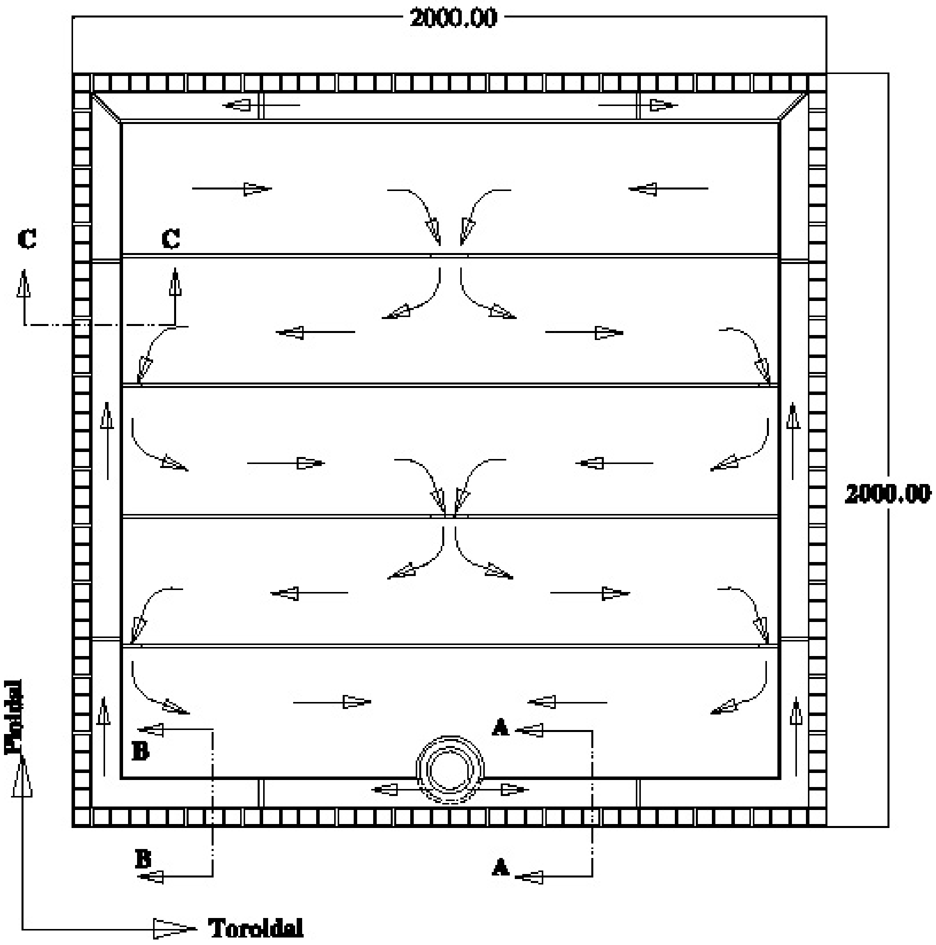
Example Flibe + FS Blanket Concept

- Self-cooled configuration where the flibe first cools the entire structure and then flows slowly in the large central ducts.
- With a flibe exit temperature of 700°C, it is believed that a cycle efficiency of >45% is achievable when coupling a Brayton cycle to the blanket via a HX.
- Such a self-cooled flibe MP=459°C) blanket can only be utilized in connection with ODS FS (with nano-size oxide particles, T_{max}~ 800°C) and requires Be pebble beds as neutron multiplier and for chemistry control.
- A dual-coolant version of the concept with He cooling the steel structure would allow for a more "conventional" reduced activation FS (T_{max}~550°C), the use of lower melting point molten salts, and the possible replacement of Be multiplier by liquid lead.

Cross-section of the Flibe Blanket Box (Front View)



Major Parameters of Different Blanket Concepts

Blanket Concepts Considered During Phase I of ARIES-CS	Self-Cooled Molten Salt	Self-Cooled Pb-17Li	Li Dual-Coolant Concept	Pb-17Li Dual-Coolant Concept	Ceramic Breeder
Breeder (form)	Flibe	Pb-17Li	Li	Pb-17Li	Li_4SiO_4 (pebble bed)
Multiplier (form)	Be(pebble bed)	None	None	None	Be(pebble bed)
Coolant	Flibe	Pb-17Li	He + self	He + self	He
Structure	ODS FS (nano-sized)	SiC_f/SiC	RAFS & ODS FS (+SiC insert if required)	RAFS & ODS FS	RAFS & ODS FS
Struct. T_{max} (°C)	700	1000	550 (RAFS) 700 (ODS FS)	550	550 (RAFS) 700 (ODS FS)
Breeder T_{max} (°C)	700	1100	800	700	950
Breeder T_{min} (°C)	550	650	500	460	
Multiplier T_{max} (°C)	750				750
Multiplier T_{min} (°C)					
Coolant T_{out} (°C)			He : 500	He : 480	610
Coolant T_{in} (°C)			He: 400	He : 300	400
Coolant P (MPa)	<0.5 (FLIBE)	2 (Pb-17Li)	He : 8	He : 14	8
Blanket thickness (m)	0.33	0.5	0.67-0.75	0.52-0.6	0.65
Avg./peak neutron wall load for analysis (MW/m^2)	2/3	2/3	2/3	2/3	3/4.5
Upper limit on neutron wall Load (MW/m^2)	3	4-5 (TBD)	4-5 (TBD)	4-5 (TBD)	~5
Surf. Heat Flux (MW/m^2)	0.5	0.5	0.5	0.5	0.5
TBR	$\geq$ 1.1	$\geq$ 1.1	$\geq$ 1.1	$\geq$ 1.1	$\geq$ 1.1
Cycle η (%)	~45	~58%	>45	~45	~42
Structural material lifetime and criteria	20 MW-a/m^2 200 dpa swelling?	18 MW-a/m^2 assuming 3% SiC burnup?	21 MW-a/m^2 200 dpa swelling?	15 MW-a/m^2 200 dpa swelling?	20 MW-a/m^2 200 dpa swelling?

What Kind of Criteria for Assessment?

From Les Waganer:

	Evaluation Metric									
	Poor	Adequate	Good	Excellent	Self-cooled **flibe**	Self-cooled **Pb-17Li**	DC **He/Li**	DC **He/Pb-17Li**	DC **He/flibe**	He-cooled **CB**
Value or Color	1	2	3	4						
Structural material **Multiplier**					ODS FS Be	SiCf/SiC None	RAFS + ODS None	RAFS + ODS None	RAFS + ODS Be or Pb	RAFS + ODS Be
Complexity (aka, Cost)	Very complex	Complex	Moderately	Simple	**4**	**4**	**3**	**3**	**3**	**1**
Safe Operation	Poor Safety	Acceptable	Passively	Very Safe	**3**	**4**	**2**	**2**	**2**	**2**
Tritium Breeding Ratio	Needs Multplr	Adequate	Good	Very Good	**2**	**2**	**2**	**2**	**2**	**2**
Thermal Efficiency, %	40-45	45-50	50-55	55-60	**2**	**4**	**3**	**2**	**2**	**1Š2**
Pumping Power	High	Moderate	Mod. Low	Low	**3**	**3**	**2**	**2**	**2**	**2**
Service Lifetime, FPY	>2	2-3	3-4	>4	**2**	**2**	**2**	**2**	**2**	**2**
Inherent Reliability	Low	Moderate	Mod High	High	**2**	**1**	**3**	**3**	**2**	**1Š2**
Development risk	Very high	High	Moderate	Low	**1**	**1**	**3**	**3**	**2Š3**	**2Š3**
Maintenance Approach										
Maintenance Time, Whole Core	Vey long	Long	Mod Log	Moderate						
Contamination Control	Very Difficult	Difficult	Moderate	Acceptable						
Complexity and Accuracy	Very	Moderate	Mod Low	Low						
				Sum	19	21	20	19	17-18	13-16

Matrix with Weighting Applied

Example Values Entered

		Evaluation Metric				Option 1		Option 2		Option 3	
		Poor	Adequate	Good	Excellent						
Value or Color	Weight	1	2	3	4	UnWtd	Weighted	UnWtd	Weighted	UnWtd	Weighted
First Wall/Blanket/Shield											
Complexity (aka, Cost)	5	Very complex	Complex	Moderately	Simple	1	5	3	15	4	20
Safe Operation	4	Poor Safety	Acceptable	Passively	Very Safe	1	4	3	12	4	16
Tritium Breeding Ratio	4	Needs Multplr	Adequate	Good	Very Good	1	4	3	12	4	16
Thermal Efficiency, %	4	40-45	45-50	50-55	55-60	1	4	3	12	4	16
Pumping Power	2	High	Moderate	Mod. Low	Low	1	2	3	6	4	8
Service Lifetime, FPY	4	>2	2-3	3-4	>4	1	4	3	12	4	16
Inherent Reliability	4	Low	Moderate	Mod High	High	1	4	3	12	4	16
Maintenance Approach											
Maintenance Time, Whole Core	3	Vey long	Long	Mod Log	Moderate	1	3	3	9	4	12
Contamination Control	3	Very Difficult	Difficult	Moderate	Acceptable	1	3	3	9	4	12
Complexity and Accuracy	4	Very	Moderate	Mod Low	Low	1	4	3	12	4	16
Sum	*37*	*37*	*74*	*111*	*148*		37		111		148

Down-Selection of Blanket Concepts

- **Ceramic Breeder Concepts**
  - Requires large heat transfer surfaces (impact on complexity, fabrication, cost)
  - Relatively thick breeding zone
  - Modest cycle efficiency
- **Molten salts**
  - In general, poor heat transfer performance
  - Limits q'' and wall load that could be accommodated for self-cooled concept
  - Self-cooled flibe blanket only feasible with advanced ODS FS.
  - DC concept with He as FW coolant preferable
- **DC Concepts (He/Liquid Breeder)**
  - He cooling needed most probably for ARIES-CS divertor (to be fully studied as part of Phase II).
  - Additional use of this coolant for the FW/structure of blankets facilitates pre-heating of blankets, serves as guard heating, and provides independent and redundant afterheat removal
  - Generally good combination of design simplicity and performance
- **Reasonable to maintain a higher pay-off, higher risk option in Phase II mix (e.g. high temperature option with SiC_f/SiC)**

Proposed Selection of Blanket Concepts for Phase II

1. **Dual Coolant concept with a self-cooled liquid breeder zone and He-cooled RAFS structure:**
   1(a) Pb-17Li with SiC-composite as electrical (and thermal) insulator between flowing LM and steel structure.
   1(b) Molten salt (possibly FLINABE with lower melting point) with the possibility of Be or lead as neutron multiplier.

2. **Self-cooled Pb-17Li blanket with SiC-composite as structural material.**

- **In principle, these concepts could all be developed in combination with either a field-period-based maintenance scheme or a port-based maintenance scheme, although for the self-cooled Pb-17Li + SiC_f/SiC option, fabrication constraints on the size of the blanket unit and the low density of the structural material makes it more amenable to a modular concept (port-based maintenance).**