Radial Build Definition for Solid Breeder System

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ARIES-CS Project Meeting
June 16 - 17, 2004
UW - Madison

Breeding Blanket Concepts

Breeder	Multiplier	Structure	FW/Blanket Coolant	Shield Coolant	VV Coolant
ARIES-CS:					
Internal VV:					
Flibe	Be	FS	Flibe	Flibe	H_2O
LiPb	–	SiC	LiPb	LiPb	H_2O
LiPb*	–	FS	He/LiPb	He	H_2O
new **Li_4SiO_4**	**Be**	**FS**	**He**	**He**	**H_2O**
External VV:					
LiPb*	–	FS	He/LiPb	He or H_2O	He
Li	–	FS	He/Li	He	He
SPPS:					
External VV:					
Li	–	V	Li	Li	He

* With or without SiC inserts.

Solid Breeder Blanket Option: Guidelines and Constraints

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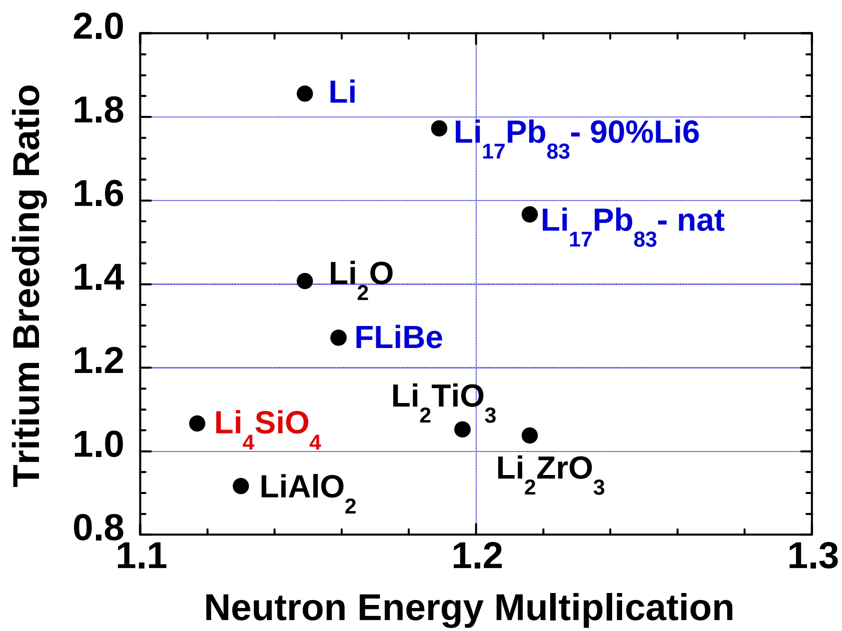
Breeder	**Lithium Ortho-silicate (Li_4SiO_4)**
Coolant	**He**
Structure	**ODS FS**
Neutron Multiplier	**Be**

- Based on well developed EU SB design, Malang's recommendations include:
  - Alternate layers of Be and SB
  - Cooling channels between adjacent layers
  - Adjust thickness of Be and SB layers to meet thermal hydraulic constraints and temperature limits
  - Adjust thickness of front Be & SB layers to allow high Γ (~ 4.5 MW/m^2)
  - 8 mm minimum thickness of SB layer (for filling reasons)
  - Single size Be and SB pebbles (60% Be/SB, 40% void/He)
  - Optimize Be:SB ratio and Li enrichment to achieve highest breeding with thinnest blanket possible
  - Use high enrichment toward back
  - Adjust blanket thickness to meet breeding requirement and protect shield

- Main findings:
  - Peak n wall loading should not exceed 4.5 MW/m^2
  - Be:SB ratio of 2:1 is near optimum for breeding
  - 65 cm thick blanket breeds sufficient T and overprotects shield.

T-M Plot

Thick Blanket, No Structure, No Multiplier
Natural Li unless Indicated



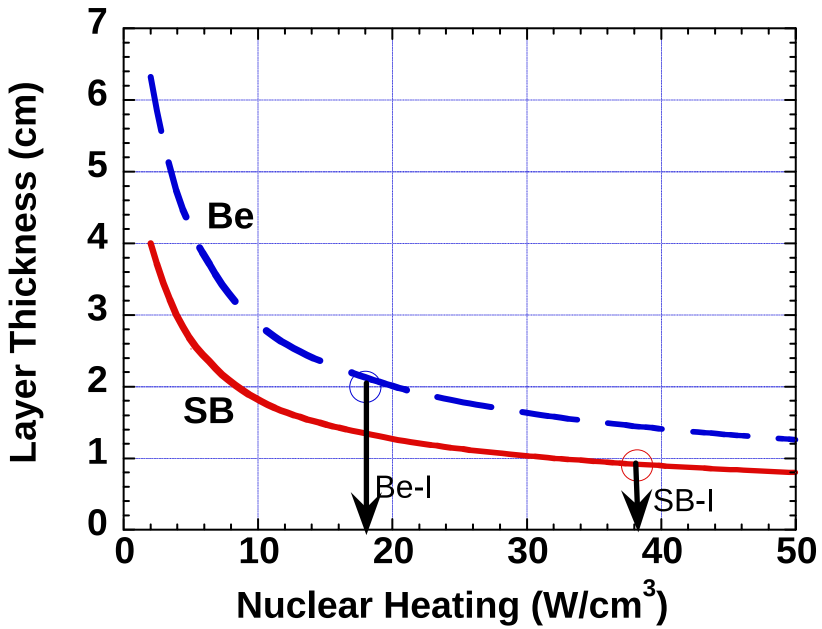
All solid breeder blankets must employ beryllium multiplier to meet breeding requirement (overall TBR $\geq$ 1.1)

SB Radial Build has been Defined on Same Groundrules, Except for Peak Γ

- **4.5 MW/m^2 peak** neutron wall loading (3 MW/m^2 used for other concepts).
- **5 cm SOL** and **2 cm** minimum VV-magnet **gap**.
- **2 cm** thick inner **coil case**.
- **31 cm thick winding packs-I/II**.
- **1.1 overall TBR for 3 FP configuration** based on 92% uniform-blanket coverage fraction, 8% shield-only zones, 5 cm thick divertor plates/baffles covering 15% of FW area.
- **$\leq$ 1% nuclear heating in LT shield and/or VV**.
- **Shield, VV, and magnet are lifetime components**
- **Radiation limits to structural components**:
  - 3% burnup to SiC/SiC composites
  - 200 dpa to FS
  - 1 He appm @ VV.
- **Radiation limits to MT S/C magnet** (same fluence as for LT S/C):
  - 10^{19} n/cm^2 fast n fluence
  - 5 mW/cm^3 local nuclear heating*
  - 10^{11} rads dose to GFF polyimide
  - 6×10^{-3} dpa to Cu stabilizer
  - 50 kW total nuclear heating.

* Dec 03 ARIES meeting, Bromberg's presentation, Page 20.

Upper Temperature Limit Controls Radial Thickness of Be and SB Layers

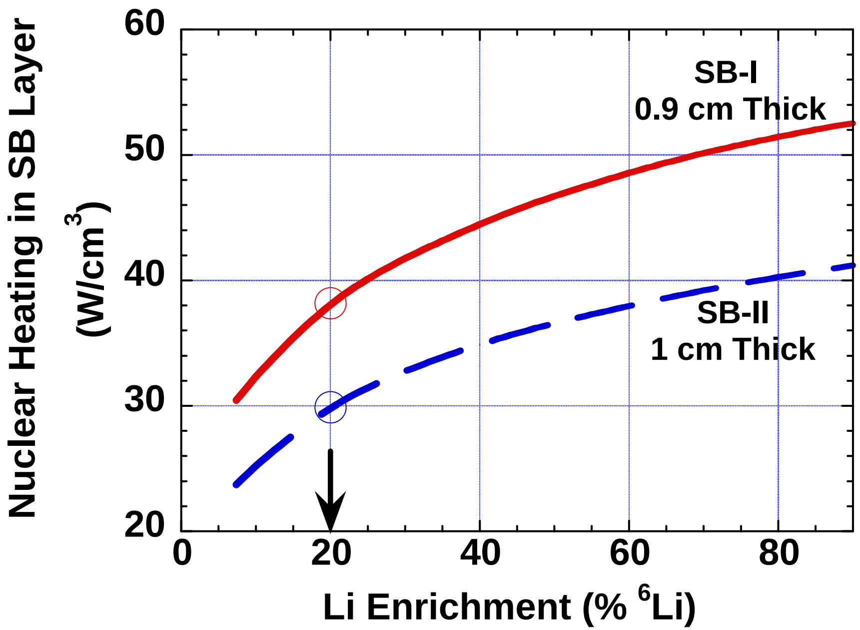


$$\Delta_{Be} = 2\sqrt{(20 / q'''_{Be})}$$

$$\Delta_{SB} = 0.8\sqrt{(50 / q'''_{SB})}$$

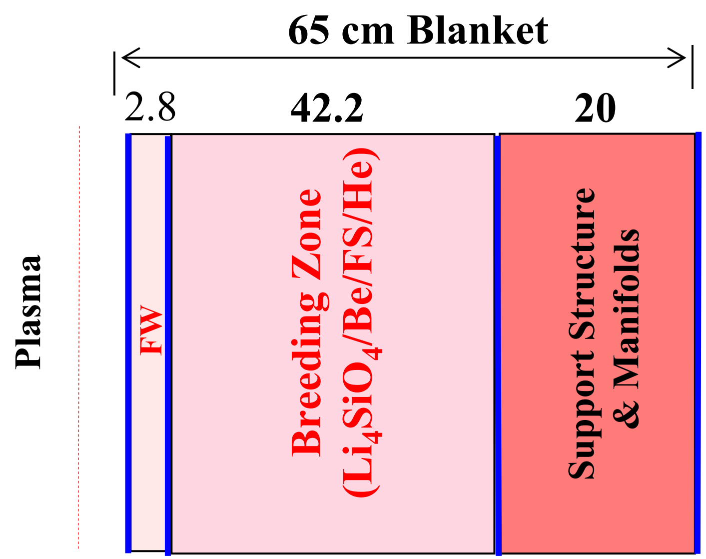
High nuclear heating at front implies thin Be and SB layers

Li Enrichment Increases Heat Deposited in SB Layers



Enrichment of individual layers adjusted to keep heating and upper temperature within limits

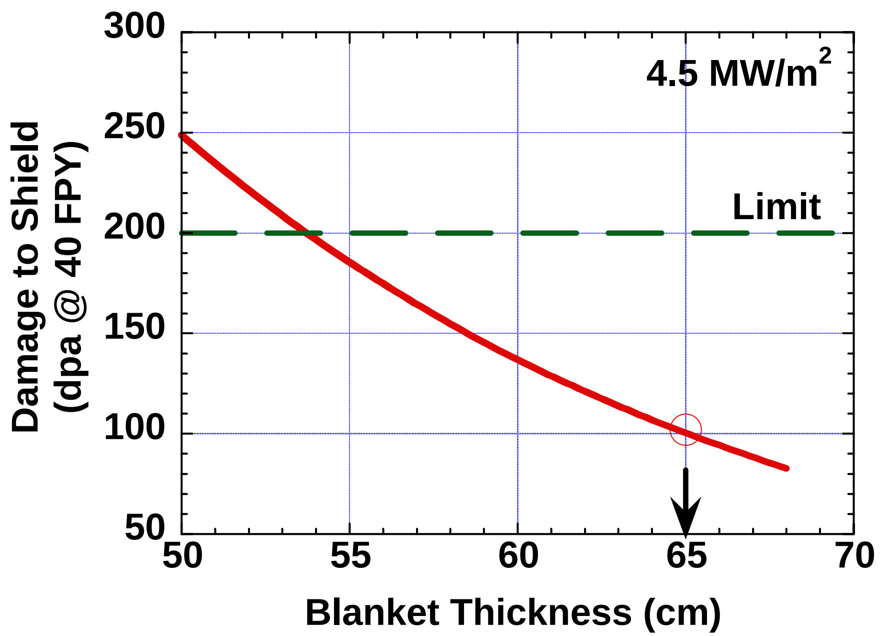
65 cm Thick Blanket Satisfies Breeding Requirement



- 42.2 cm breeding zone contains many layers :

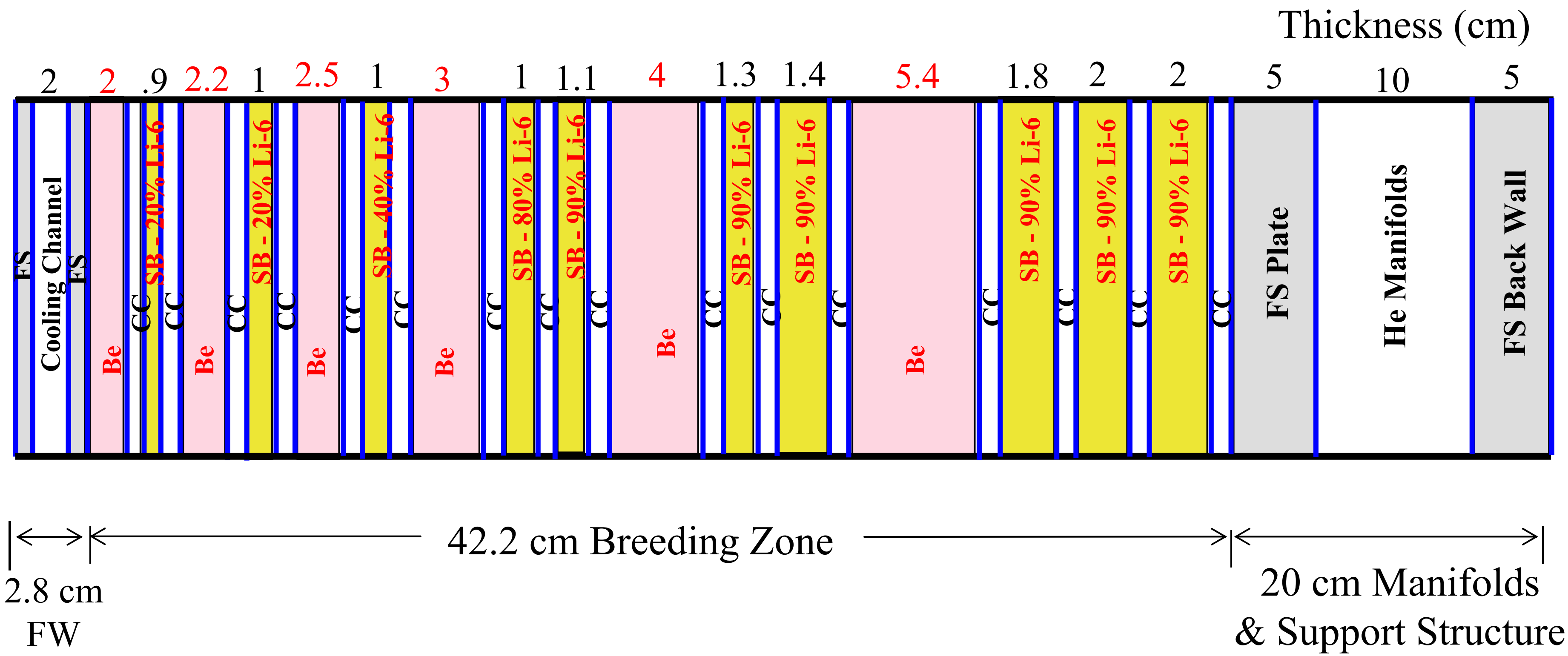
10	SB Layers (0.9 - 2 cm thick, 20 - 90% enrichment)
6	Be Layers (2 - 5.4 cm thick)
16	Cooling channels (0.6 cm thick)
32	**Layers**

65 cm Thick Blanket Overprotects Shield



Li enrichment has no impact on damage at shield

Schematic of 65 cm Thick Blanket
(4.5 MW/m² peak)

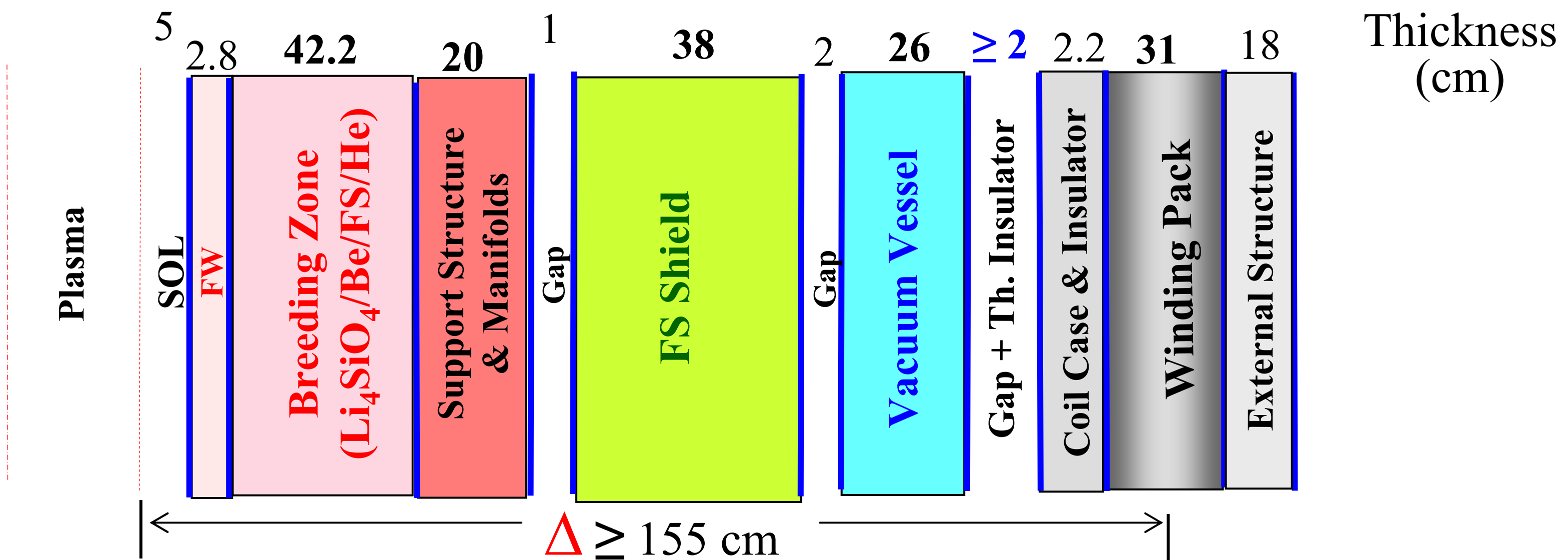


0.6 cm Thick Cooling Channel (CC)

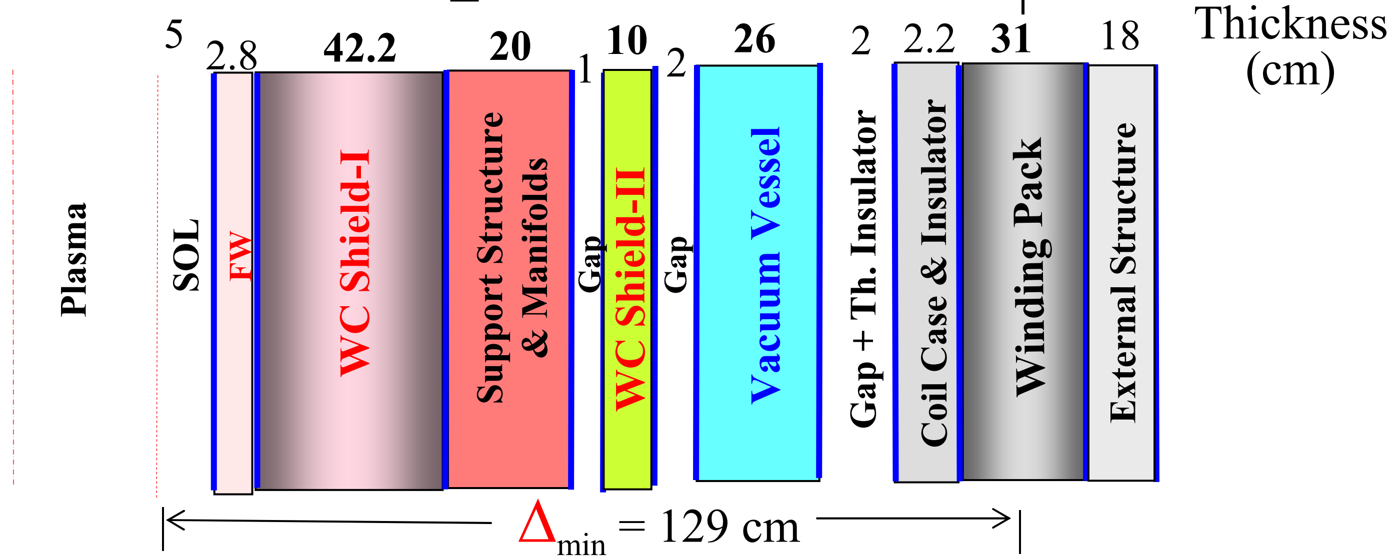
Li_4SiO_4/Be/FS/He Radial Build

(Water-Cooled **Internal** VV, 4.5 MW/m^2 peak)

Blanket Zones



Shield Only Zones



Boundary between WC-shields will be adjusted to meet design requirements

Li_4SiO_4/Be/FS/He Composition

Component	Composition	
Blanket	10% Li_4SiO_4 (20- 90% enriched Li) 17% Be 30% FS Structure 43% He Coolant	
HT FS/He Shield	15% FS Structure 75% Borated Steel Filler 10% He Coolant	
HT WC/He Shield-I & Manifolds	30% FS Structure 45% WC Filler 25% He Coolant	
LT WC Shield-II	15% FS Structure 75% WC Filler 10% He Coolant	
Vacuum Vessel	27% FS Structure 23% Borated Steel Filler 50% H_2O Coolant	
Winding Pack I & II (BSSCO magnet is not available yet)	12.7% MgB_2 45.5% Cu 15.5% He @ 15 k 17.3% 316-SS 9.0% GFF poly.	9.6% NbTi 54.1% Cu 21.8% LHe @ 4 k 5.5% 316-SS 9.0% GFF poly.

Preliminary Blanket Cost Estimate

	Volume (m^3)	Mass (Tons)	Unit Cost ($/kg)	Blanket Cost ($M)
Be	100	190	~600	110
SB	60	150	~600 ?	90
FS	190	1,470	70*	100
				300 ⇒ 10 mills/kWh

+ Replacement Cost ~15-20 mills/kWh

- **Expensive solid breeder blanket**.
- For comparison, FS-based **liquid** breeder blankets cost ~ $50M (< 2 mills/kWh) and replacement cost is ~4 mills/kWh.

* Higher fabrication cost expected.

Nominal Radial Distance Varies Widely with Blanket Concept

(Blanket/Shield Dimensions for CAD Drawings)

	Δ (m)			
ARIES-CS:				
Internal VV:	**Blanket/Shield/VV/Gaps**		**Plasma – Mid Coil**	
Flibe/FS/Be	**1.07**	(min)	**1.32**	(min)
LiPb/SiC	1.15		1.40	
LiPb/FS/He	1.24		1.49	
new Li_4SiO_4/Be/FS/He	**1.30**	(max)	**1.55**	(max)
External VV:	**Blanket/Shield/Gaps**			
LiPb/FS/He/B-H_2O	1.28		1.53	
LiPb/FS/He	1.60		1.85	
Li/FS/He	1.79	(max)	2.04	(max)
SPPS*:				
External VV:				
Li/V	1.20		1.96	

* 15 cm SOL, 36 cm half winding pack, 15 cm thick cryostat, and 8 cm wide shield-magnet gap.

Minimum Radial Distance Varies within 18 cm with Blanket Concept

(Δ_{min} for Systems Code Analysis)

	Δ_{min} (m)	
ARIES-CS:		
Internal VV:	**WC-Shield/VV**	**Plasma – Mid Coil**
Flibe/FS/Be	0.86 (min)	1.11 (min)
LiPb/SiC	0.89	1.14
LiPb/FS/He	0.93	1.18
new Li_4SiO_4/Be/FS/He	**1.04** (max)	**1.29** (max)
External VV:	**WC-Shield**	
LiPb/FS/He/B-H_2O	0.87	1.12
LiPb/FS/He	0.93	1.18
Li/FS/He	0.91	1.16
SPPS:		
External VV:		
Li/V	–	–

- Solid breeder blanket has largest Δ_{min}
- 18 cm difference in Δ_{min} translates into ~1.1 m change in R

Key Parameters for System Analysis (3 FP Configuration)

	Flibe/FS/Be	LiPb/SiC	SB/FS/Be	LiPb/FS	Li/FS
Δ_{min}	1.11	1.14	1.29	1.18	1.16
TBR	1.1	1.1	1.1	1.1	1.1
Energy Multiplication (M_n)	1.2	1.1	**1.3**	1.15	1.13
Thermal Efficiency (η_{th})	45%	55-60%	45%	~45%	~45%
FW Lifetime (FPY)	6.5	6	4.4	5	7
System Availability	~85%	~85%	85%	~85%	~85%

- Solid breeder blanket provides highest M_n.
- System analysis will assess impact of Δ_{min}, M_n and η_{th} on COE.

Conclusions

- Main features of SB blanket:
  - Peak n wall loading should not exceed 4.5 MW/m^2
  - Be:SB ratio of 2:1 is near optimum for breeding
  - 65 cm thick blanket breeds sufficient T and overprotects shield.

- Other features:
  - \+ Largest M_n ⇒ Low COE
  - – Largest Δ_{min} ⇒ Large machine
  - – Complex design (32 layers)
  - – High fabrication cost
  - – Expensive blanket
  - – High replacement cost.

  (Largest Δ_{min} through High replacement cost) ⇒ High COE

- Design complexity should be assigned high weighting factor for blanket selection criteria.

- **Recommendation**: use liquid breeder particularly for stellarators to simplify design, reduce size, and lower cost.

Future Plan

- Initiate LOCA analysis for LiPb/FS blanket system.

- Document work and submit 4 TOFE papers:

  1- **Benefits of Radial Build Minimization and Requirements Imposed on ARIES Compact Stellarator Design**
  L. El-Guebaly, R. Raffray, S. Malang, J. Lyon, L.P. Ku and the ARIES Team

  2- **Initial Activation Assessment for ARIES Compact Stellarator Power Plant**
  L. El-Guebaly, P. Wilson, D. Paige and the ARIES Team

  3- **Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants**
  L. El-Guebaly, P. Wilson, D. Paige and the ARIES Team

  4- **Views on Neutronics and Activation Issues Facing Thick Liquid-Protected IFE Chambers**
  L. El-Guebaly and the ARIES Team