ARIES-CS
Radial Build Definition and Nuclear System Characteristics

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US / Japan Workshop on Power Plant Studies
January 24 - 25, 2006
UCSD

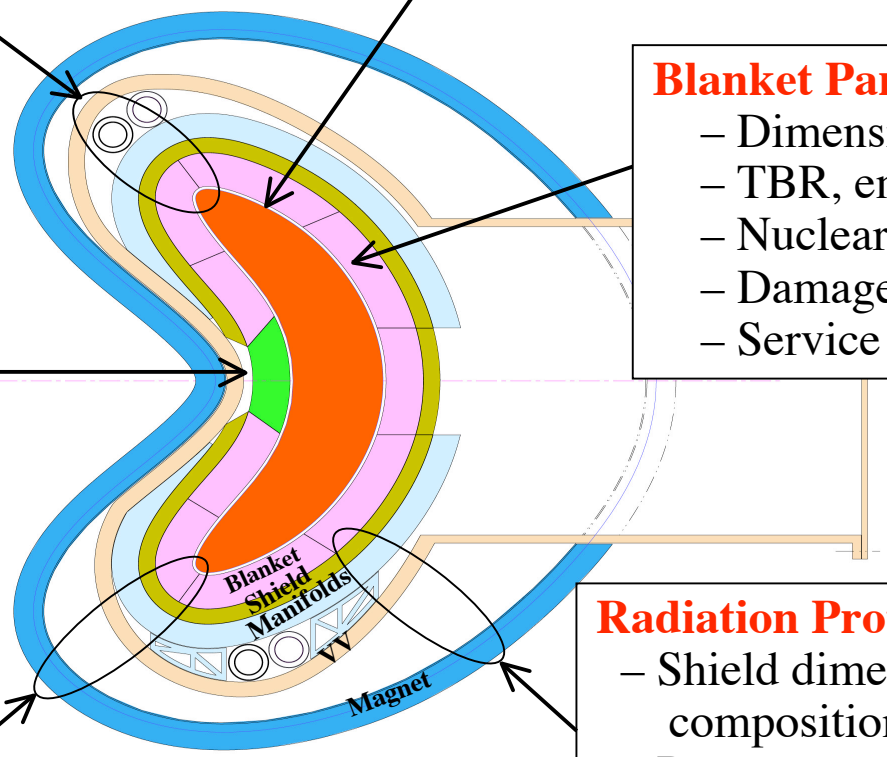
Nuclear Areas of Research

Radial Build Definition:
- Dimension of all components
- Optimal composition

Neutron Wall Loading Profile:
- Toroidal & poloidal distribution
- Peak & average values

Blanket Parameters:
- Dimension
- TBR, enrichment, M_n
- Nuclear heat load
- Damage to FW
- Service lifetime

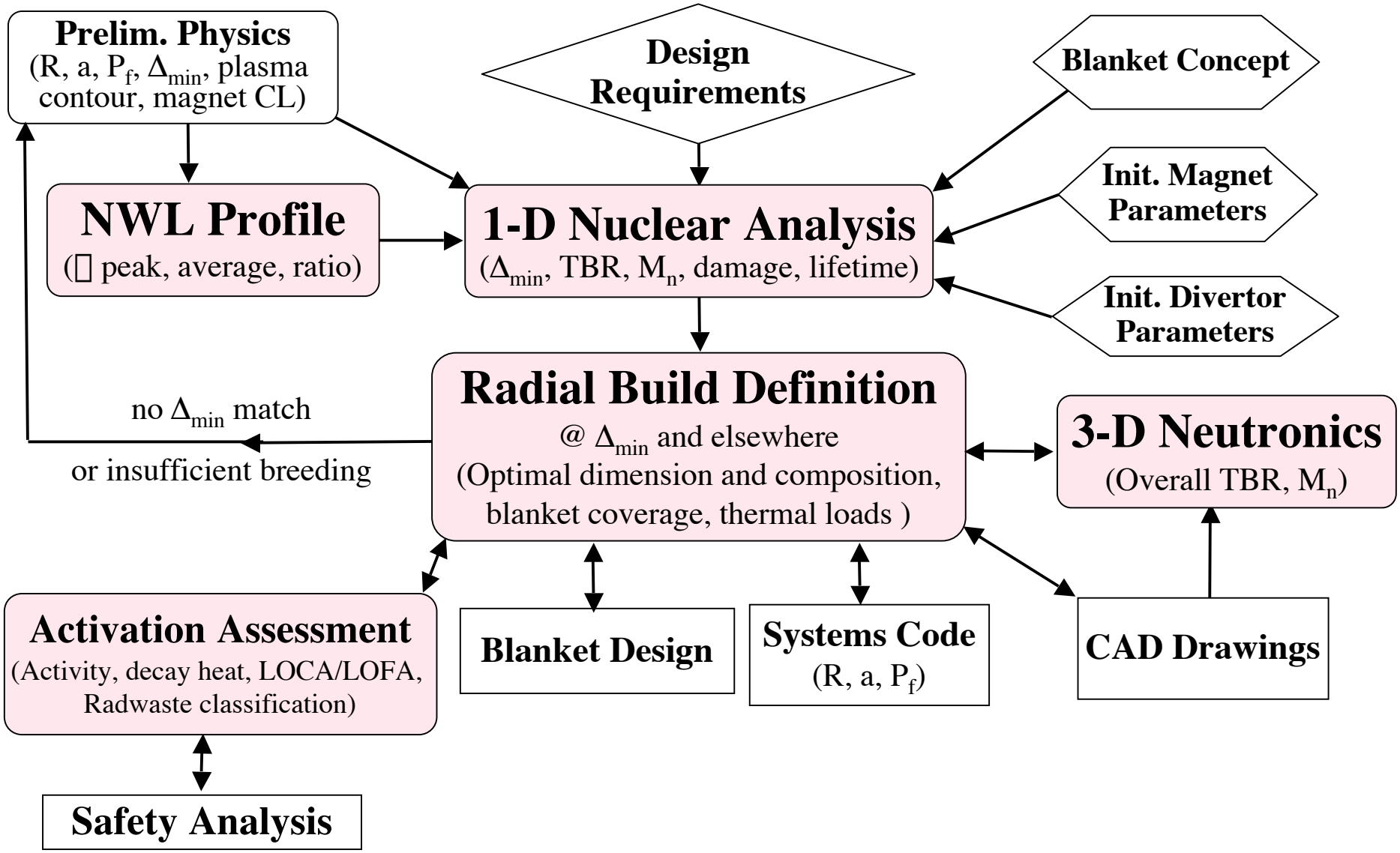
High-performance shielding module at θ_{min}



Activation Issues:
- Activity and decay heat
- Thermal response to LOCA/LOFA events
- Radwaste management

Radiation Protection:
- Shield dimension & optimal composition
- Damage profile at shield, manifolds, VV, and magnets
- Streaming issues

Nuclear Task Involves Active Interaction with many Disciplines



Stellarators Offer Unique Engineering Features and Challenges

- Minimum radial standoff at $\square_{min}$ controls machine size and cost.
  - Well optimized radial build particularly at $\square_{min}$
- Sizable components with low shielding performance (such as blanket and He manifolds) should be avoided at $\square_{min}$.
- Could design tolerate shield-only module (no blanket) at $\square_{min}$?
  Impact on TBR, overall size, and economics?
- Compactness mandates all components should provide shielding function:
  - Blanket protects shield
  - Blanket and shield protect manifolds and VV
  - Blanket, shield, and VV protect magnets
- Highly complex geometry mandates developing new approach to directly couple CAD drawings with 3-D neutronics codes.
- Economics and safety constraints control design of all components from beginning.

ARIES-CS Requirements Guide
In-vessel Components Design

Overall TBR (for T self-sufficiency)	1.1	
Damage to Structure (for structural integrity)	200	dpa - advanced FS
	3%	burn up - SiC
Helium Production @ Manifolds and VV (for reweldability of FS)	1	appm
S/C Magnet (@ 4 K):		
Fast n **fluence** to Nb_3Sn ($E_n > 0.1$ MeV)	10^{19}	n/cm^2
Nuclear **heating**	2	mW/cm^3
dpa to Cu stabilizer	$6x10^{-3}$	dpa
Dose to electric insulator	$> 10^{11}$	rads
Machine Lifetime	40	FPY
Availability	85%	

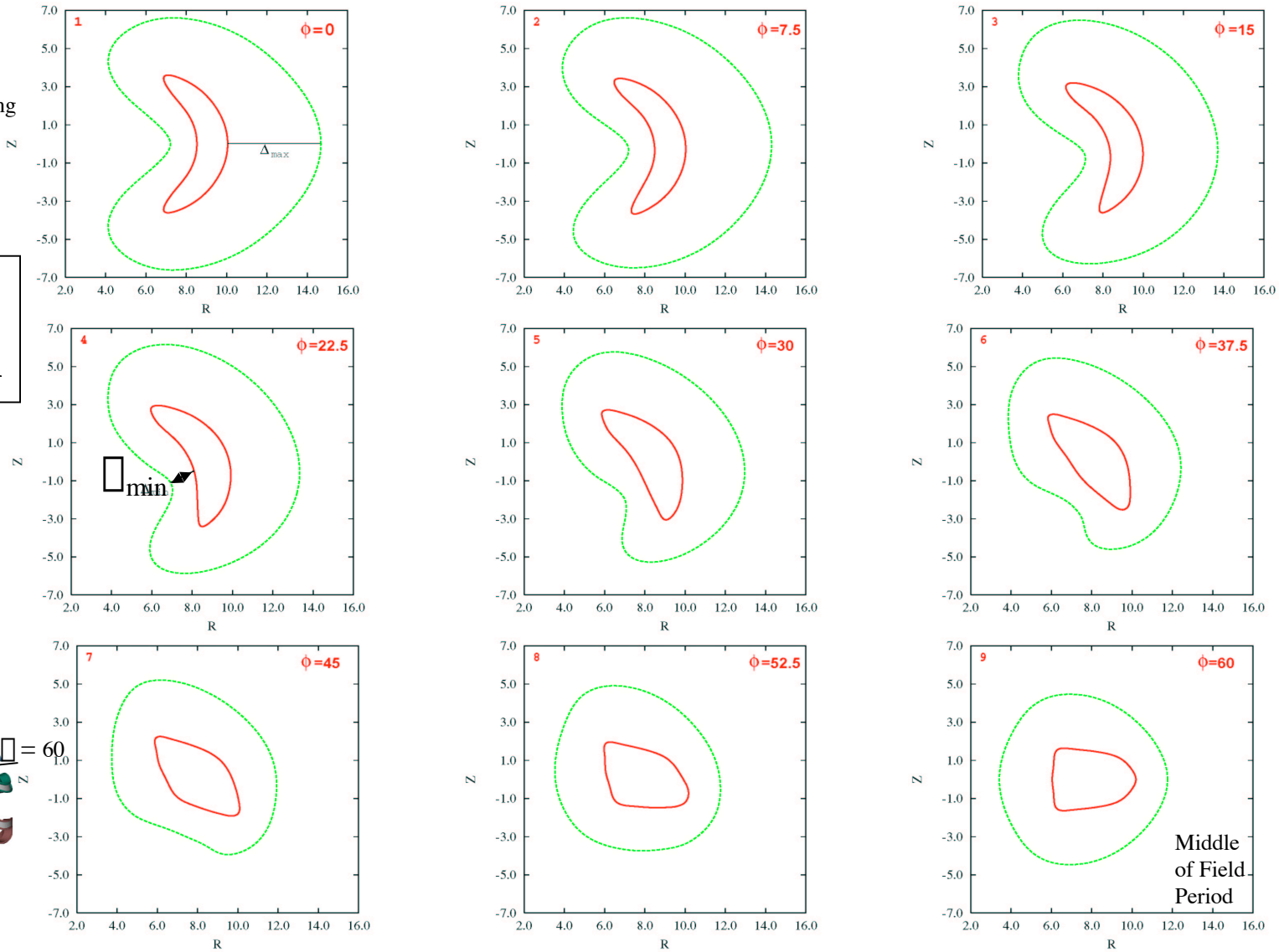
Reference Dual-cooled LiPb/FS Blanket Selected with Advanced LiPb/SiC as Backup

Breeder	Multiplier	Structure	FW/Blanket Coolant	Shield Coolant	VV Coolant
Internal VV:					
Flibe	Be	FS	Flibe	Flibe	H_2O
LiPb (backup)	**–**	**SiC**	**LiPb**	**LiPb**	**H_2O**
LiPb (reference)	**–**	**FS**	**He/LiPb**	**He**	**H_2O**
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

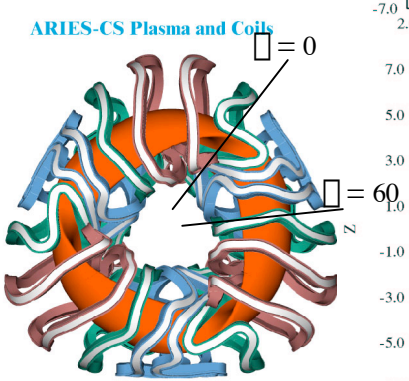
FW Shape Varies Toroidally and Poloidally - a Challenging 3-D Modeling Problem

Beginning of Field Period

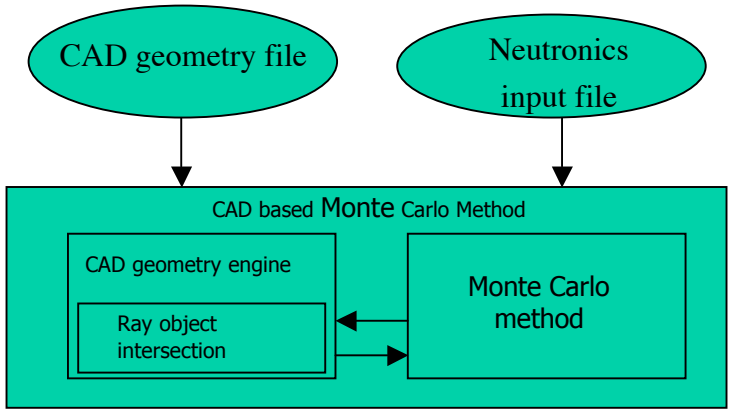
3 FP
R = 8.25 m



Middle of Field Period

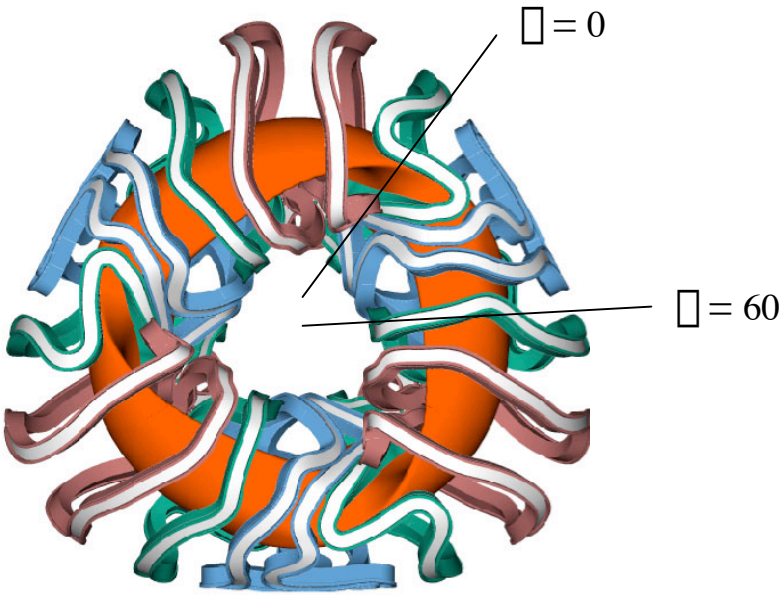


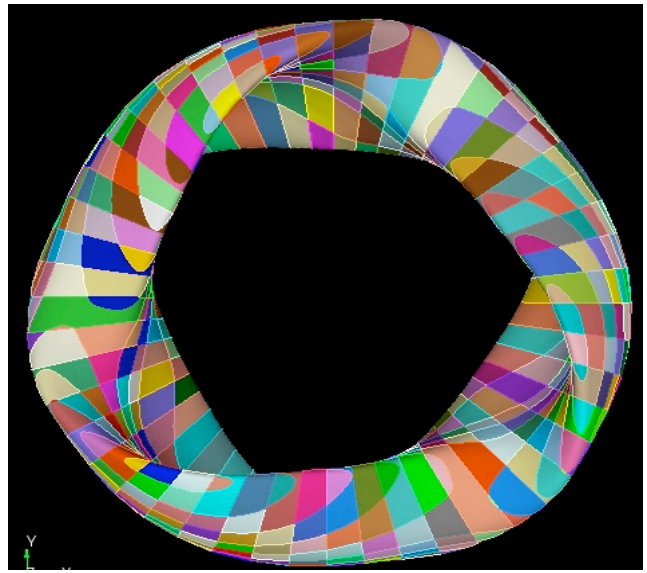
UW Developed CAD/MCNP Coupling Approach to Model ARIES-CS for Nuclear Assessment

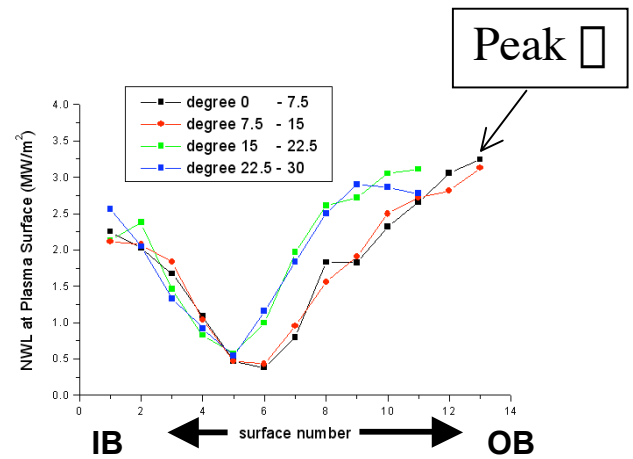


- Only viable approach for ARIES-CS 3-D neutronics modeling.
- Geometry and ray tracing in CAD; radiation transport physics in MCNPX.
- This unique, superior approach gained international support.
- Ongoing effort to benchmark it against other approaches developed abroad (in Germany, China, and Japan).
- DOE funded UW to apply it to ITER - relatively simple problem.

3-D Neutron Wall Loading Profile Using CAD/MCNP Coupling Approach

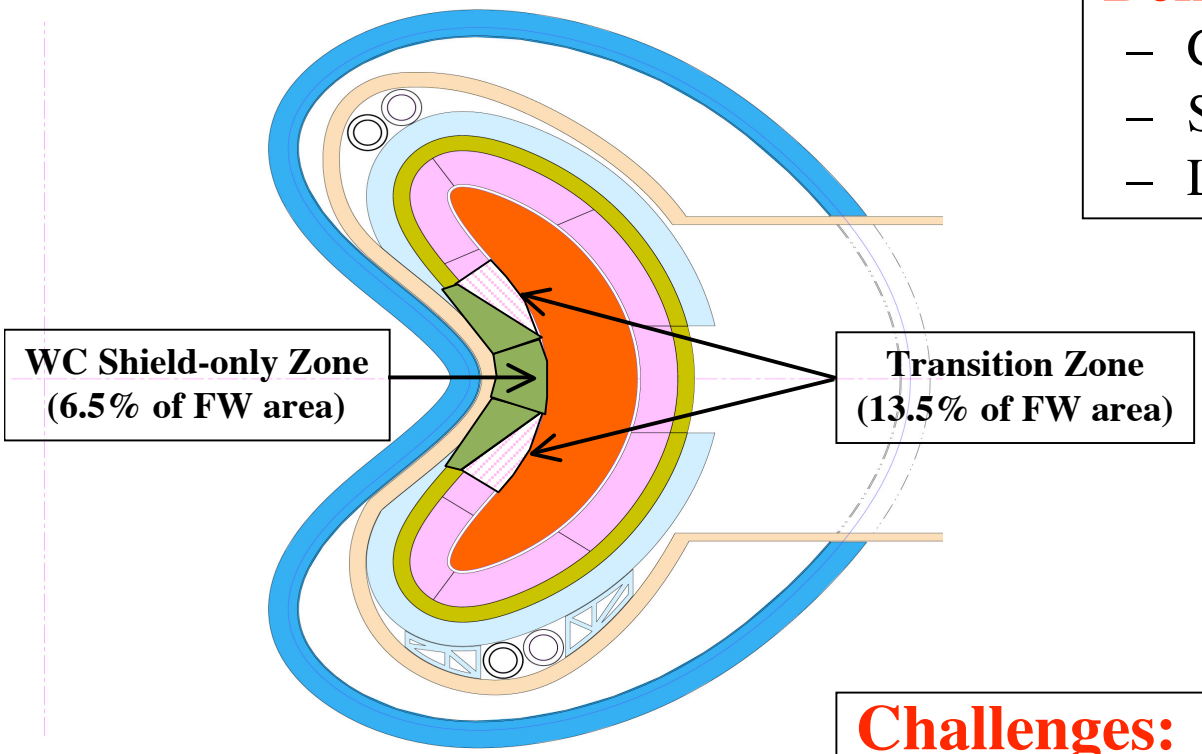






- R = 8.25 m design.
- Neutrons tallied in discrete bins:
  - Toroidal angle divided every 7.5°.
  - Vertical height divided into 0.5 m segments.
- Peak ~3 MW/m^2 at OB midplane of = 0°
- Peak to average = 1.52

Novel Shielding Approach Helps Achieve Compactness



Benefits:

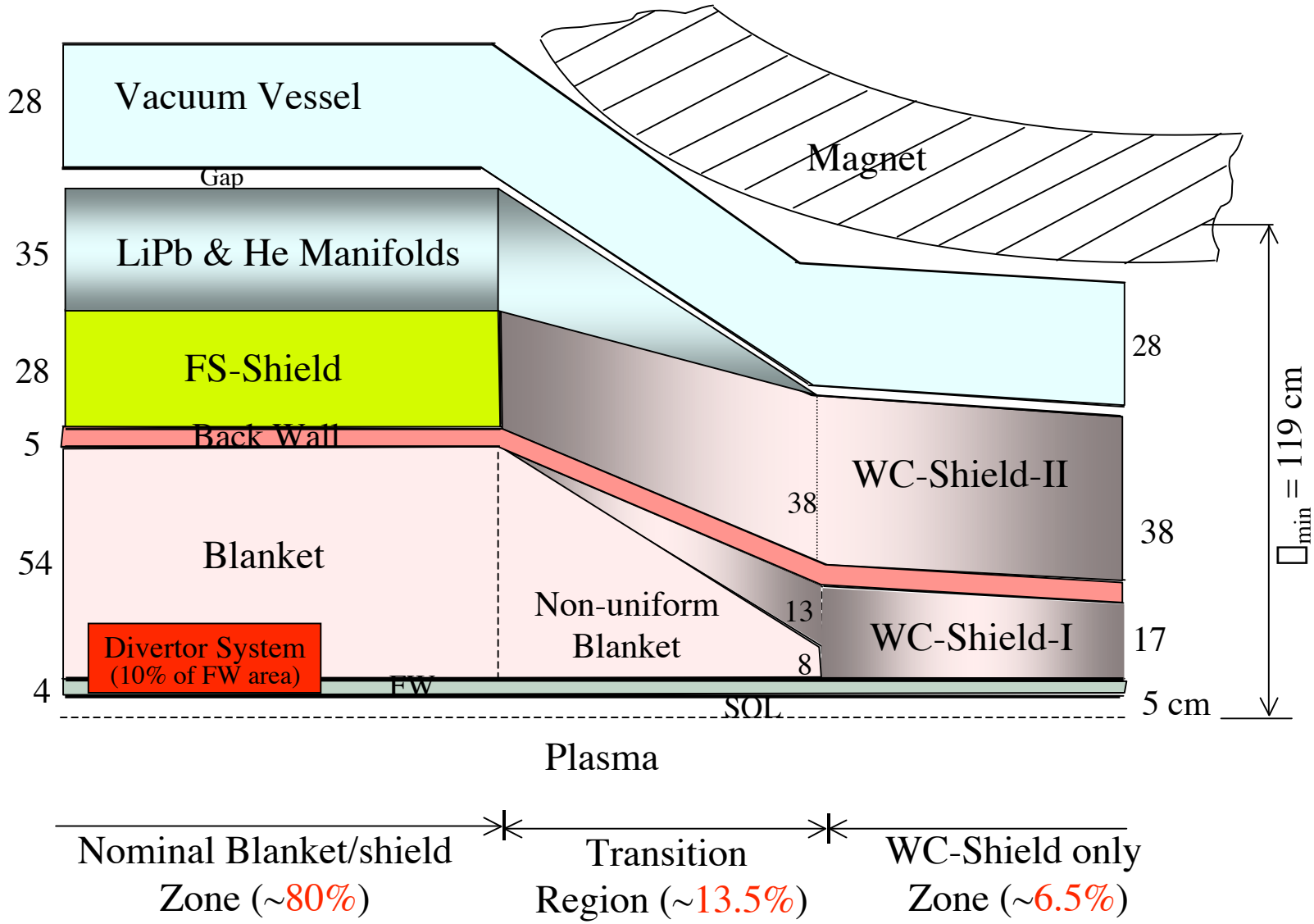
- Compact radial build at $\square_{min}$
- Small R and low B_{max}
- Low COE.

Challenges:

- Integration of shield-only and transition zones with surrounding blanket.
- Routing of coolants to shield-only zones.
- Higher WC decay heat compared to FS.

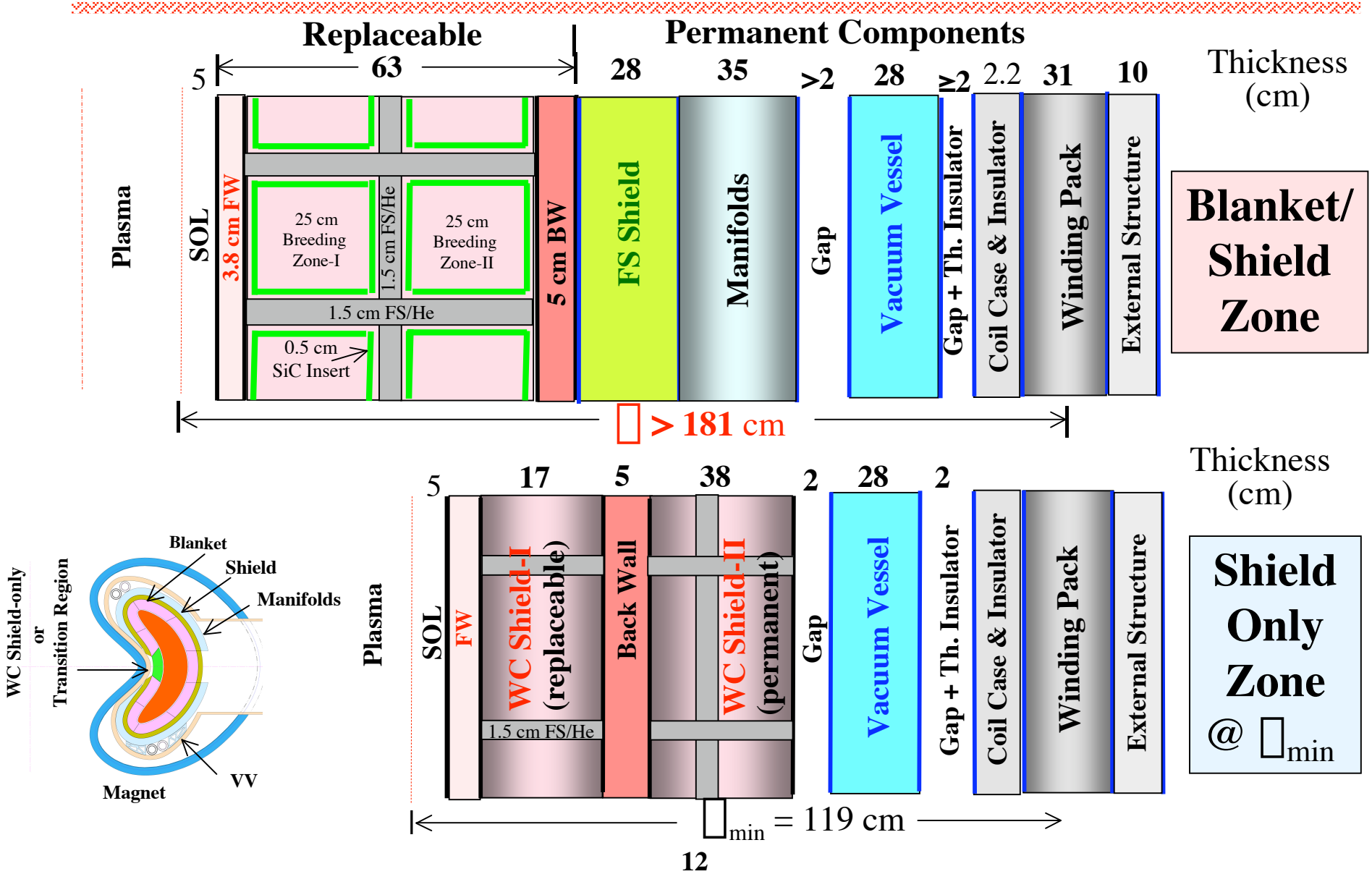
Toroidal / Radial Cross Section

(R = 8.25 m)

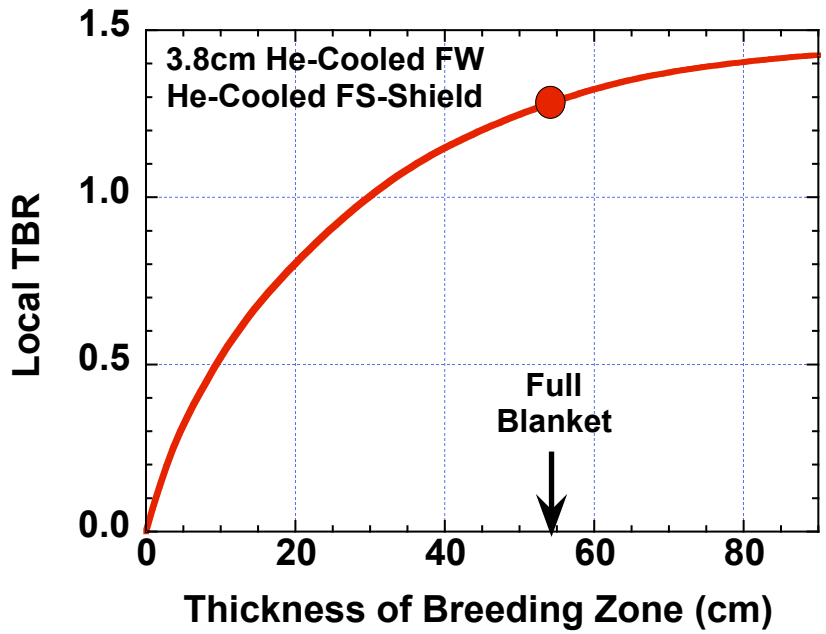


Radial Build Satisfies Design Requirements

(3 MW/m^2 peak □)



Blanket Design Meets Breeding Requirement



- Local TBR approaches 1.3
- 3-D analysis confirmed 1-D local TBR estimate for **full** blanket coverage.
- Uniform and non-uniform blankets sized to provide 1.1 overall TBR based on 1-D results combined with blanket coverage. To be confirmed with detailed 3-D model.

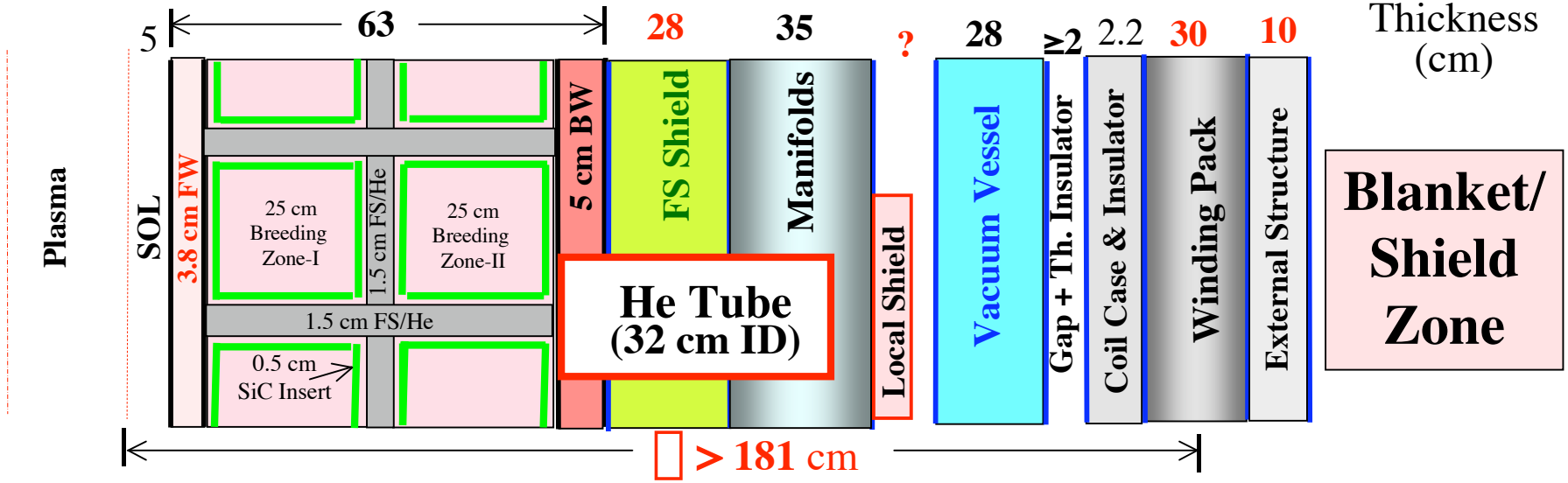
Preliminary 3-D Results Using CAD/MCNP Coupling Approach

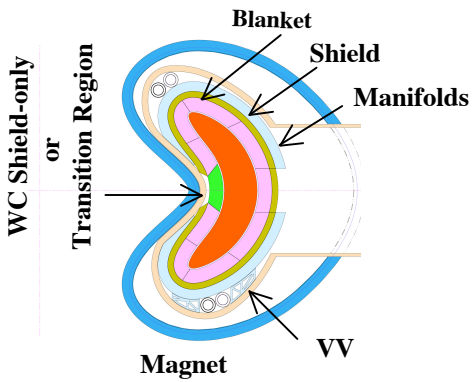
Model*	1-D	3-D	
Local TBR	1.285	1.316	± 0.61%
Energy multiplication (M_n)	1.14	1.143	± 0.49%
Peak dpa rate (dpa/FPY)	40	39.4	± 4.58%
FW/B lifetime (FPY)	5	5.08	± 4.58%
Nuclear heating (MW):			
FW	156	145.03	±1.33%
Blanket	1572	1585.03	±1.52%
Back wall	13	9.75	± 6.45%
Shield	71	62.94	± 2.73%
Manifolds	18	19.16	± 5.49%
Total	1830	1821.9	± 0.49%

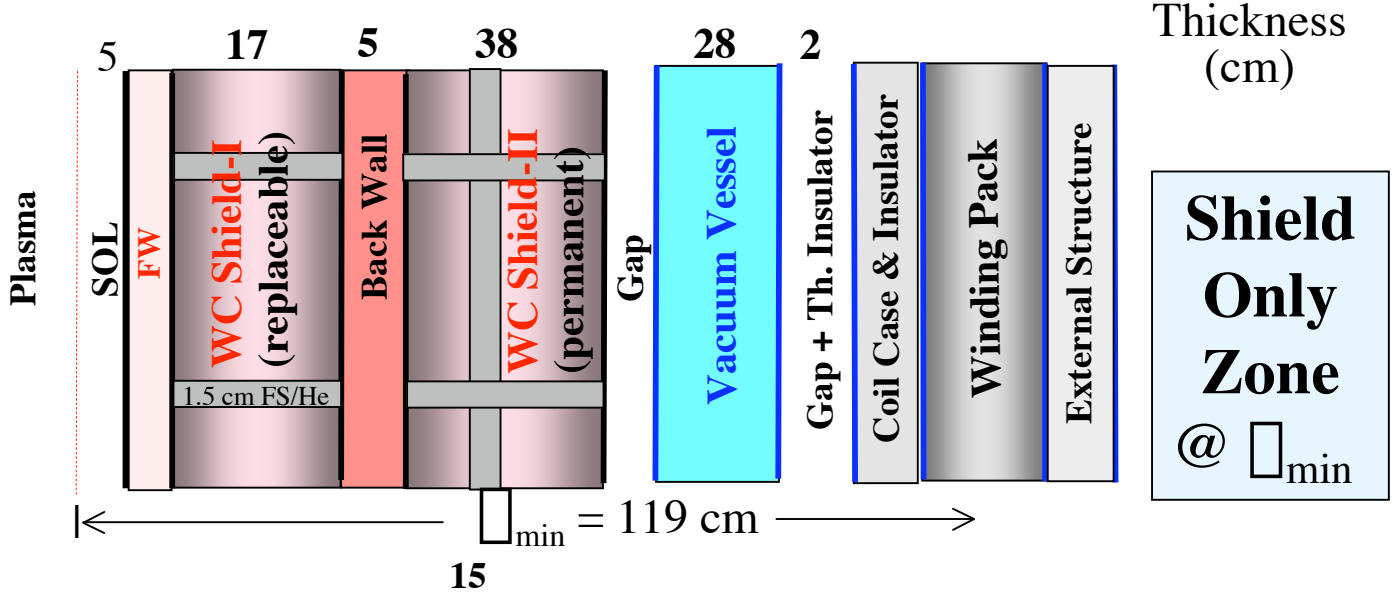
Future 3-D analysis will include blanket variation, divertor system and penetrations to confirm 1.1 overall TBR and M_n.

* Homogenized components. Uniform blanket everywhere. No divertor. No penetrations. No gaps.

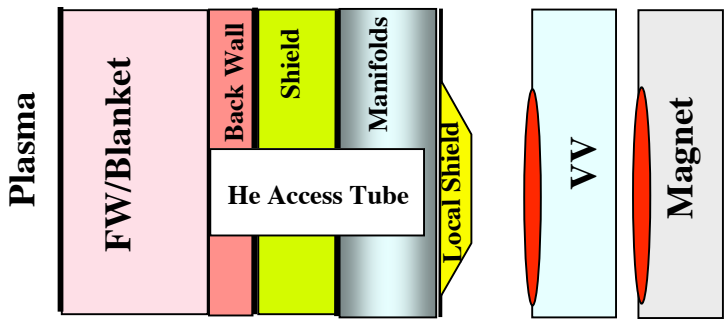
He Access Tubes Raise Streaming Concern



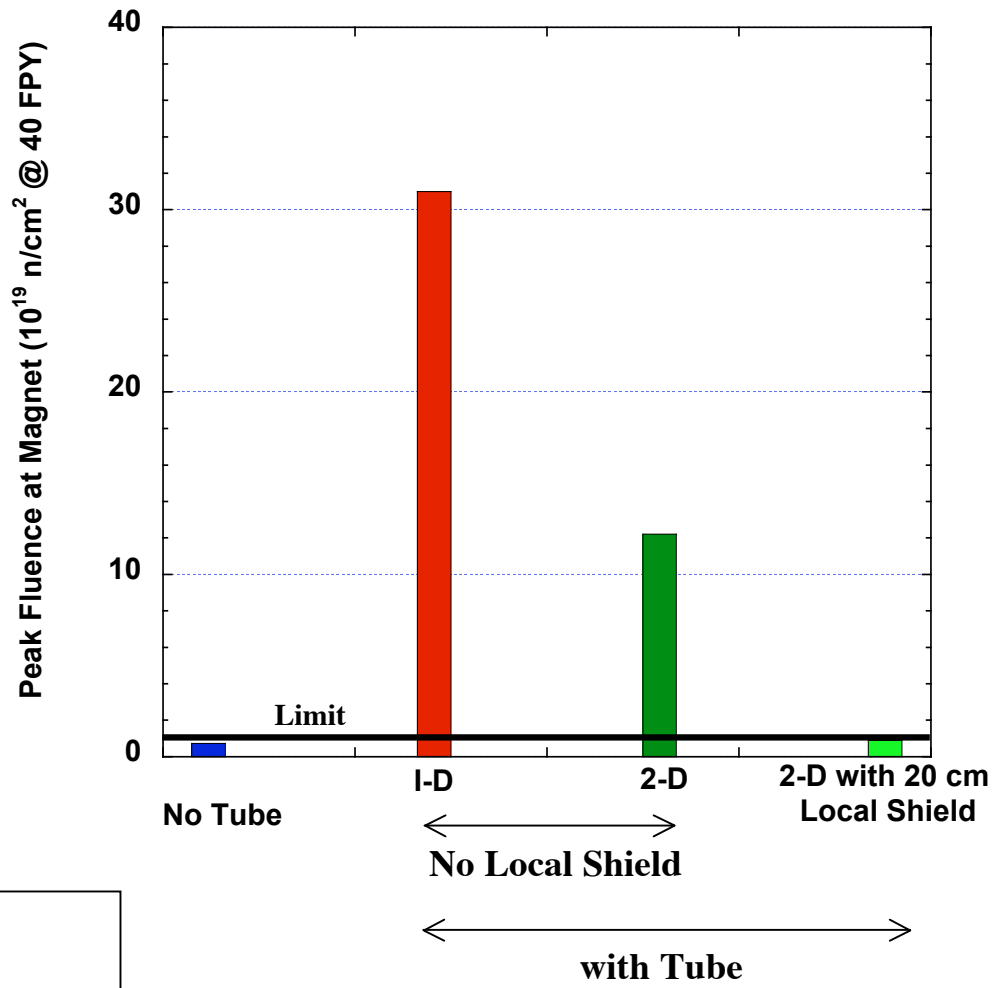




Local Shield Helps Solve Neutron Streaming Problem



Hot spots at
VV and magnet



Ongoing 3-D analysis will optimize dimension of local shield

Key Design Parameters for Economic Analysis

	LiPb/FS/He (reference)	LiPb/SiC (backup)
$\square_{min}$	1.19	1.14
Overall TBR	1.1	1.1
Energy Multiplication (M_n)	1.14	1.1
Thermal Efficiency ($\square_{th}$)	40-45%*	55-63%*
FW Lifetime (FPY)	5	6
System Availability	~85%	~85%

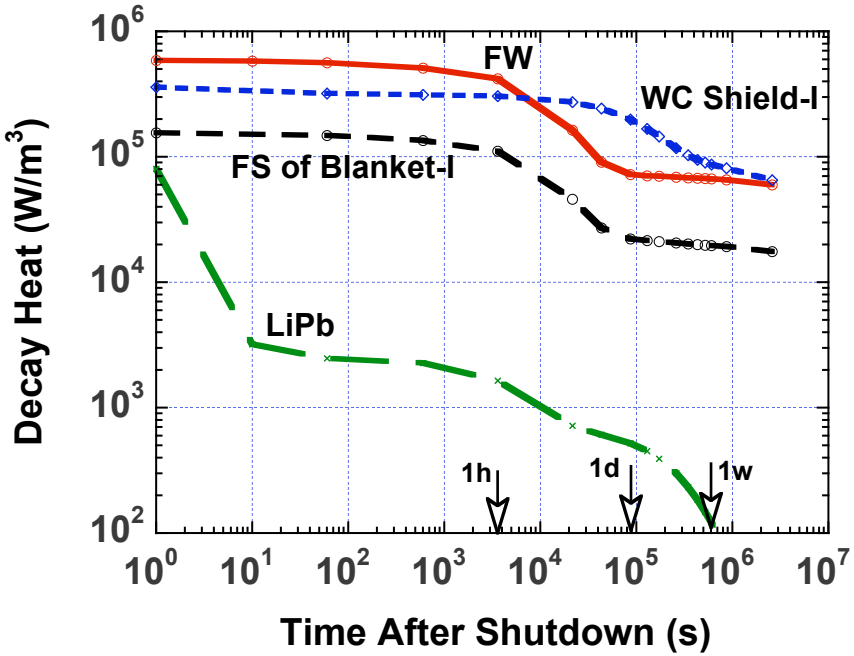
* Depending on peak $\square$.

Integral system analysis will assess impact of $\square_{min}$, M_n, and $\square_{th}$ on COE

Activation Assessment

- **Main concerns:**
  - Decay heat of FS and WC components.
  - Thermal response of blanket/shield during LOCA/LOFA.
  - Waste classification:
    - Low or high level waste?
    - Any cleared metal?
  - Radwaste stream.

Decay Heat

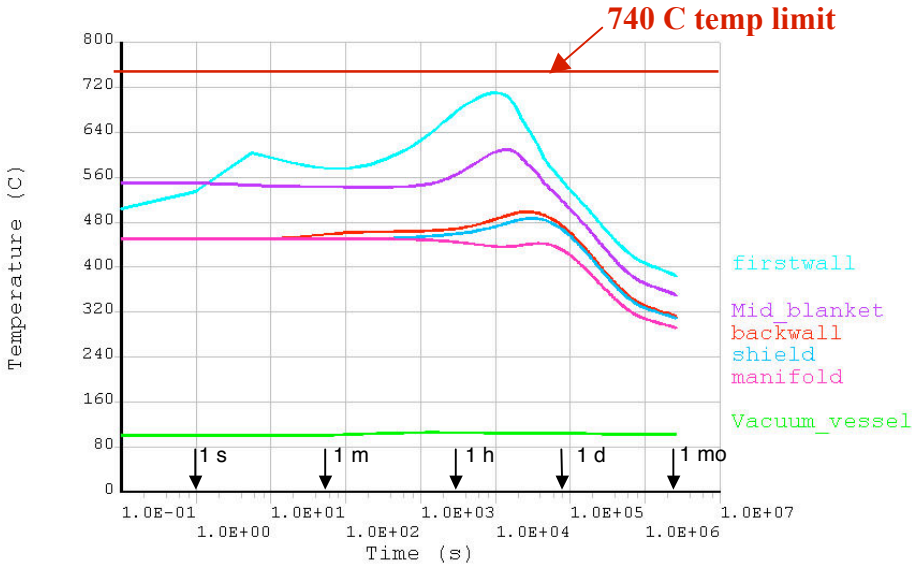


WC decay heat dominates at 3 h after shutdown

Thermal Response during LOCA/LOFA Event

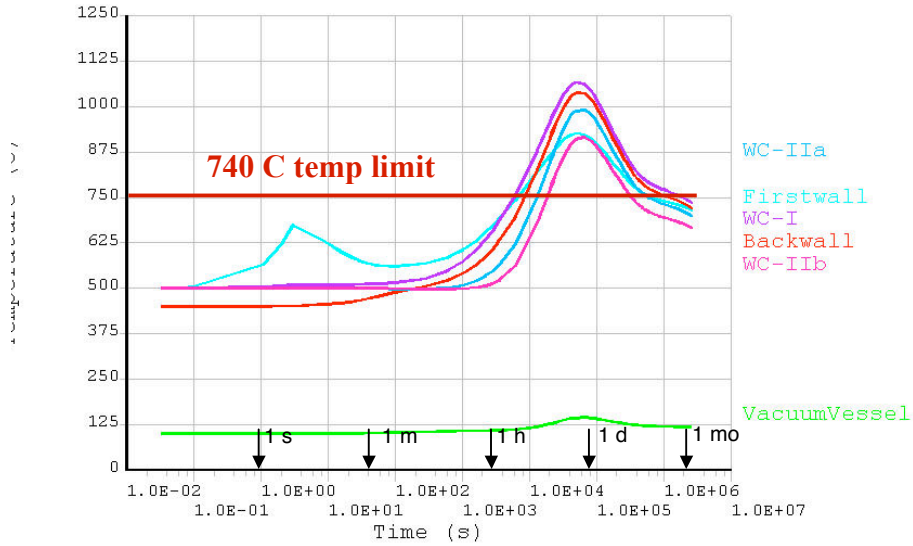
Nominal Blanket/Shield

T_{max} ~ 711 °C



Shield-only Zone

T_{max} ~ 1060 °C



- 3-coolant system rare LOCA/LOFA event (< 10^{-8}/y)
- Severe accident scenario: He and LiPb LOCA in **all** blanket/shield modules & water LOFA in VV.
- For blanket, FW temperature remains below 740 °C limit.
- WC shield modules may need to be replaced. More realistic accident scenario will be assessed.

Waste Management Approach

- **Options**:
  - **Disposal** in LLW or HLW repositories
  - **Recycling** – reuse within nuclear facilities
  - **Clearing** – release to commercial market, if CI < 1.

- **Repository capacity is limited**:
  - **Recycling** should be top-level requirement for fusion power plants
  - **Transmute** long-lived radioisotopes in special module
  - **Clear** majority of activated materials to minimize waste volume.

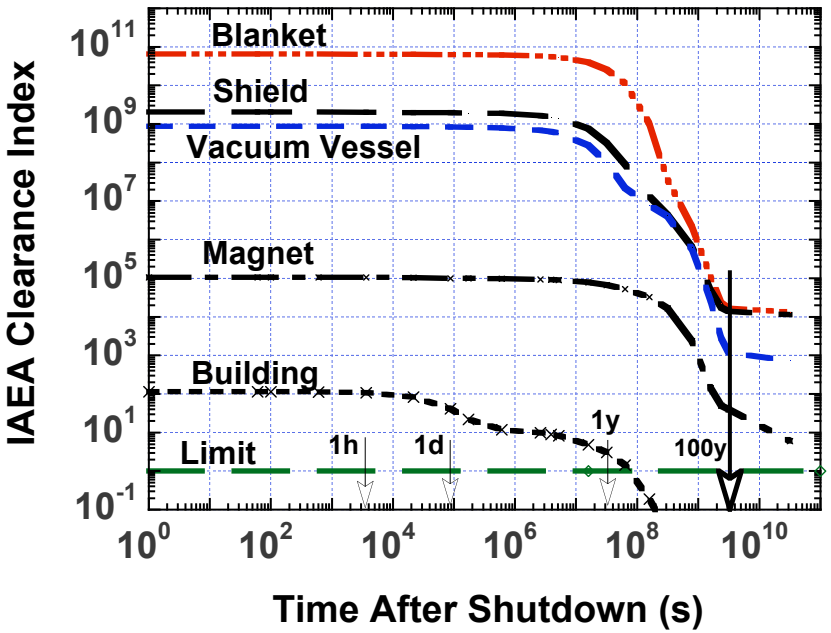
ARIES-CS Generates Only Low-Level Waste

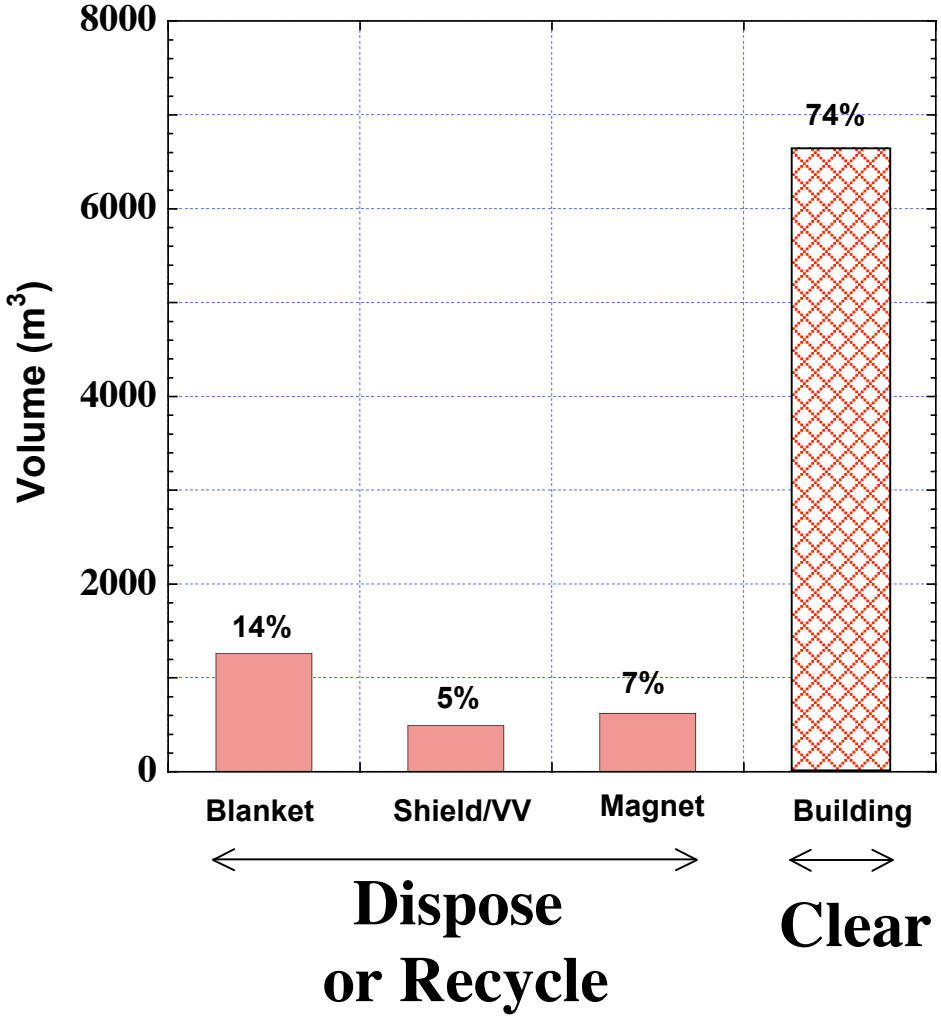
	WDR
Replaceable Components:	
FW/Blanket-I	0.4
WC-Shield-I	0.9
Permanent Components:	
WC-Shield-II	0.3
FS Shield	0.7
Vacuum Vessel	0.05
Magnet	< 1
Confinement building	<< 0.1

LLW (WDR < 1) qualifies for near-surface disposal or, preferably, recycling

Majority of Waste (74%) can be Cleared from Regulatory Control

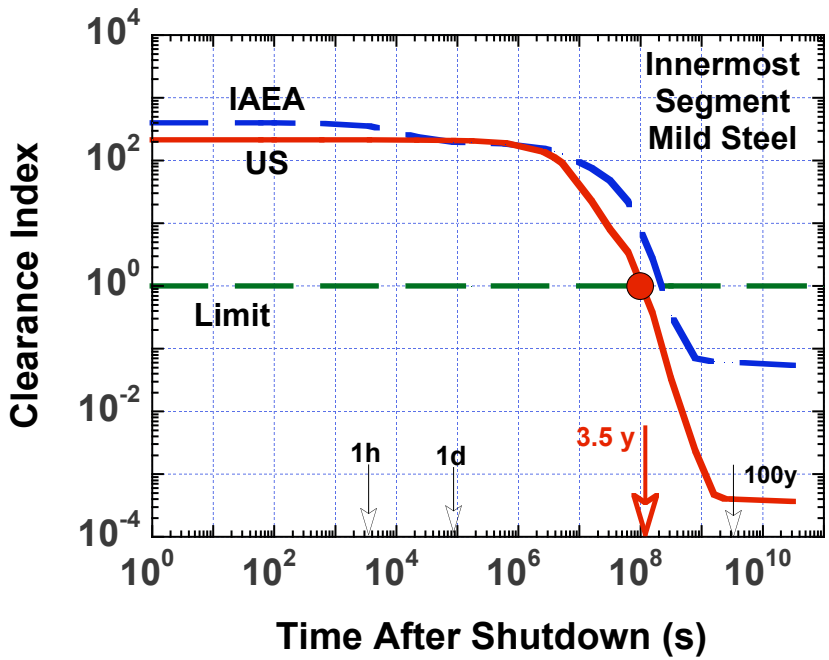
In-vessel components cannot be cleared

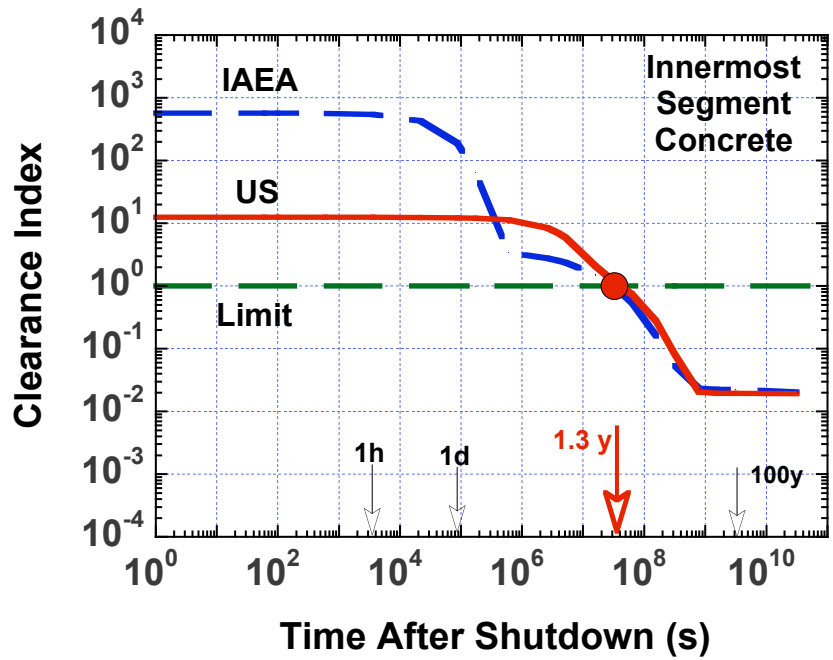




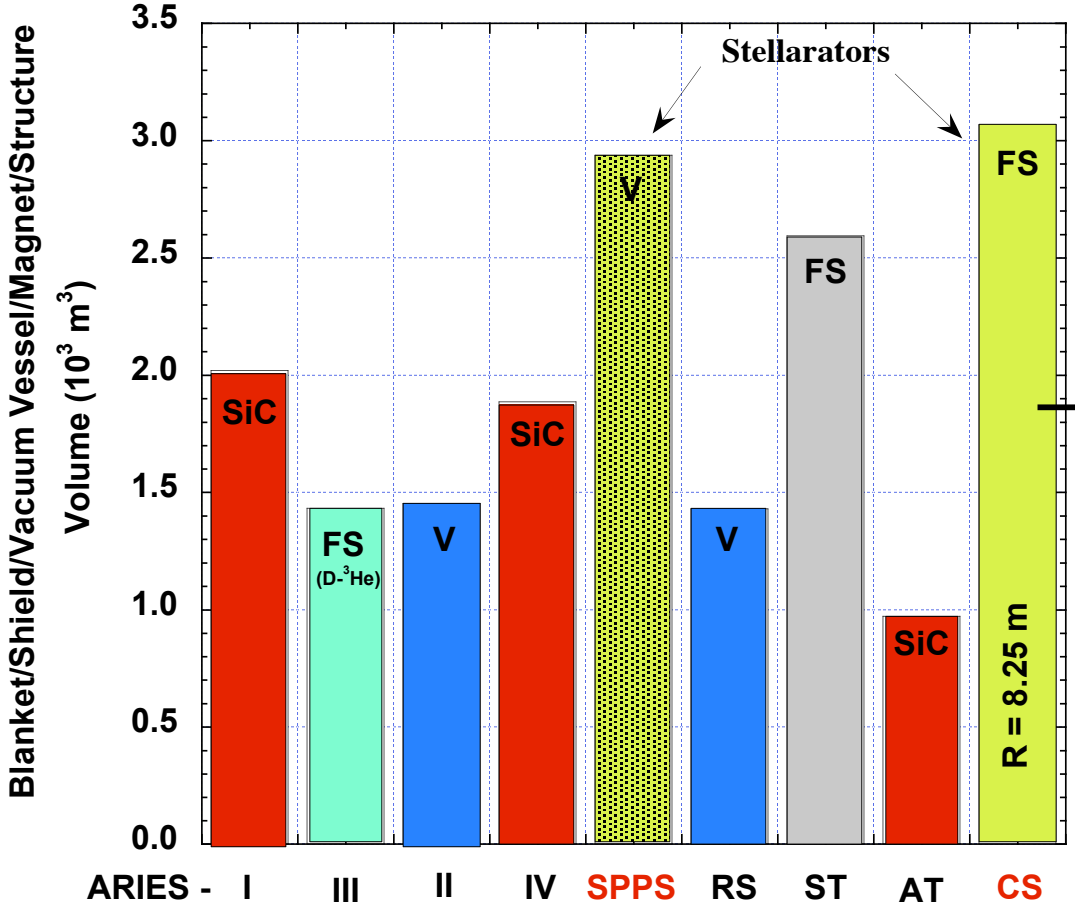
Building Constituents can be Cleared 1-4 y after Plant Decommissioning

Building composition: 15% Mild Steel, 85% Concrete

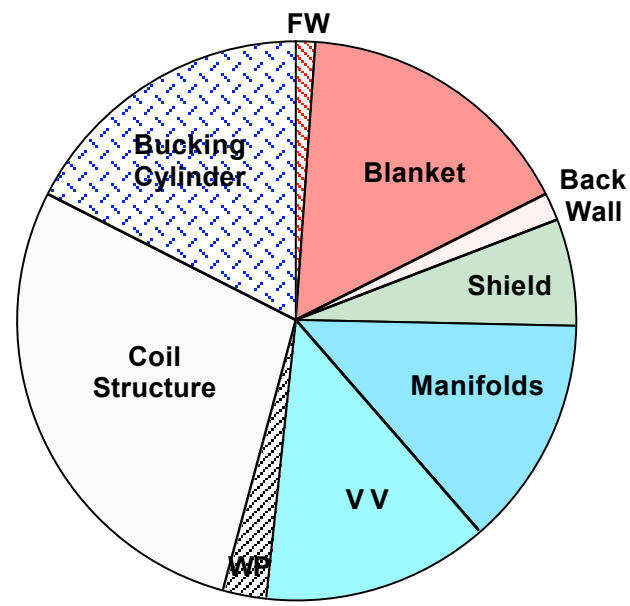




Stellarators Generate Large Radwaste Compared to Tokamaks

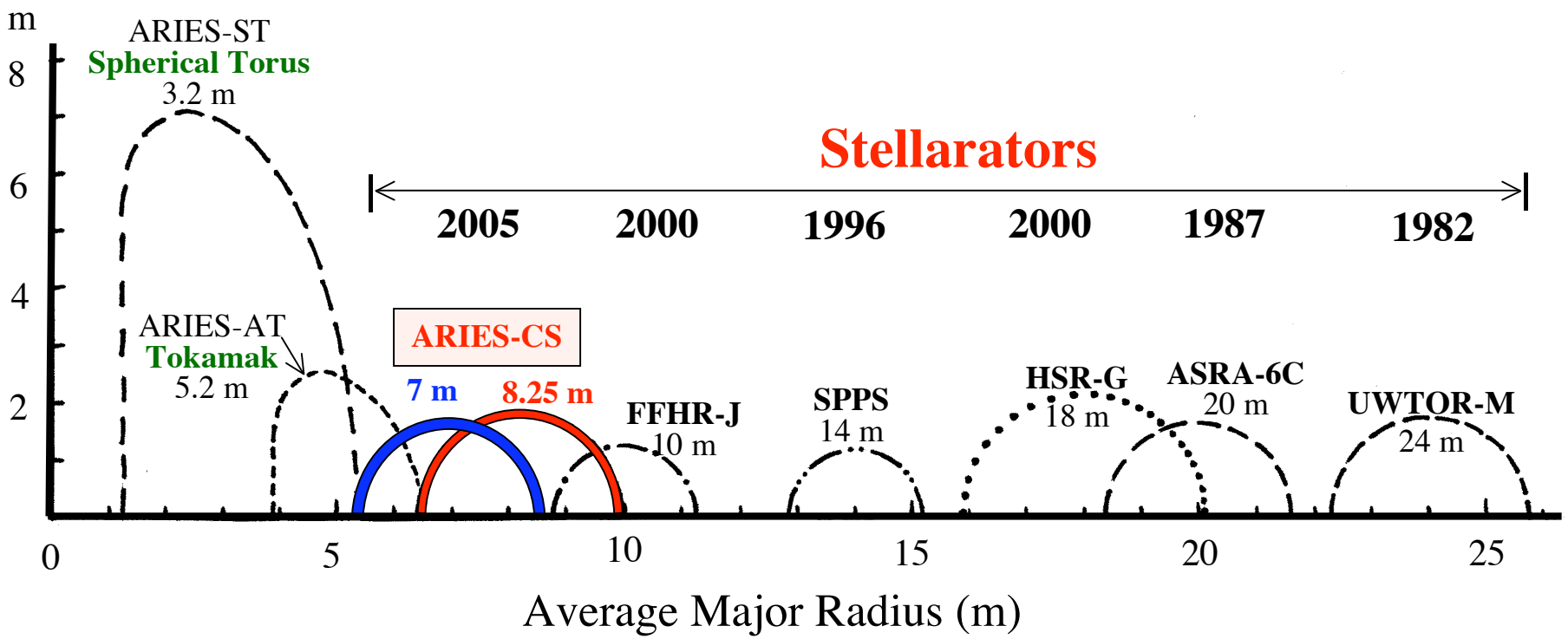


not compacted, no replacements



Means to reduce ARIES-CS radwaste are being pursued
(more compact machine with less coil support and bucking structures)

Well Optimized Radial Build Contributed to Compactness of ARIES-CS



Over past 25 y, stellarator major radius more than halved by advanced physics and technology, dropping from 24 m for UWTOR-M to 7-8 m for ARIES-CS, approaching R of advanced tokamaks.

Concluding Remarks

- Novel shielding approach developed for ARIES-CS. Ongoing study is assessing benefits and addressing challenges.
- CAD/MCNP coupling approach developed specifically for ARIES-CS 3-D neutronics modeling.
- Combination of shield-only zones and non-uniform blanket presents best option for ARIES-CS.
- Proposed radial build satisfies design requirements.
- No major activation problems identified for ARIES-CS.
- At present, ongoing ARIES-CS study is examining more compact design ($R < 8$ m) that needs further assessment.

ARIES-CS Publications

L. El-Guebaly, R. Raffray, S. Malang, J. Lyon, and L.P. Ku, "Benefits of Radial Build Minimization and Requirements Imposed on ARIES-CS Stellarator Design," Fusion Science & Technology, **47**, No. 3, 432 (2005).

L. El-Guebaly, P. Wilson, and D. Paige, "Initial Activation Assessment of ARIES Compact Stellarator Power Plant," Fusion Science & Technology, **47**, No. 3, 440 (2005).

M. Wang, D. Henderson, T. Tautges, L. El-Guebaly, and X. Wang, "Three -Dimensional Modeling of Complex Fusion Devices Using CAD-MCNP Interface," Fusion Science & Technology, **47**, No. 4, 1079 (2005).

L. El-Guebaly, P. Wilson, and D. Paige, "Status of US, EU, and IAEA Clearance Standards and Estimates of Fusion Radwaste Classifications," University of Wisconsin Fusion Technology Institute Report, UWFDM-1231 (December 2004).

L. El-Guebaly, P. Wilson, and D. Paige, "Evolution of Clearance Standards and Implications for Radwaste Management of Fusion Power Plants," Journal of Fusion Science & Technology, **49**, 62-73 (2006).

M. Zucchetti, L. El-Guebaly, R. Forrest, T. Marshall, N. Taylor, K. Tobita, "The Feasibility of Recycling and Clearance of Active Materials from Fusion Power Plants," Submitted to ICFRM-12 conference at Santa Barbara (Dec 4-9, 2005).

L. El-Guebaly, R. Forrest, T. Marshall, N. Taylor, K. Tobita, M. Zucchetti, "Current Challenges Facing Recycling and Clearance of Fusion Radioactive Materials," University of Wisconsin Fusion Technology Institute Report, UWFDM-1285. Available at: http://fti.neep.wisc.edu/pdf/fdm1285.pdf

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J. Lyon, L.P. Ku, P. Garabedian, L. El-Guebaly, and L. Bromberg, "Optimization of Stellarator Reactor Parameters," Fusion Science & Technology, **47**, No. 3, 4414 (2005).

R. Raffray, S. Malang, L. El-Guebaly, and X. Wang, "Ceramic Breeder Blanket for ARIES-CS," Fusion Science & Technology, **48**, No. 3, 1068 (2005).