Overview of ARIES-CS In-Vessel Components: Integration of Nuclear, Economics, and Safety Constraints in Compact Stellarator Design

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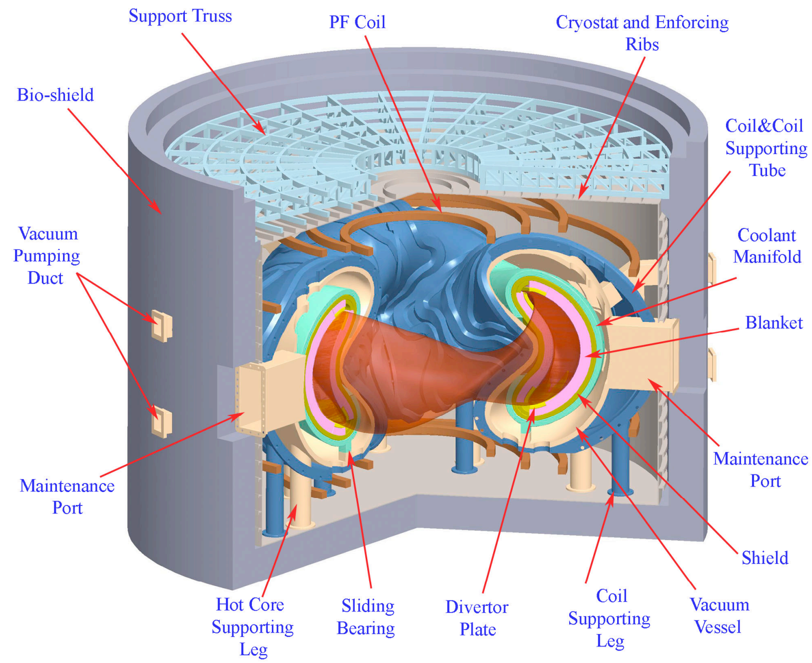
ARIES Compact Stellarator*

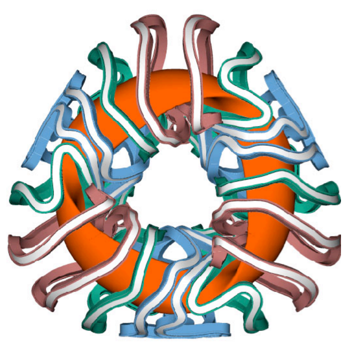
Study aimed at reducing stellarators' size by:

- Developing compact configuration with low aspect ratio and advanced physics & technology
- **Optimizing minimum plasma-coil distance (Δ_{min}) through rigorous nuclear assessment.**



3 Field Periods Configuration#

Average Major Radius	**7.75 m**
Average Minor Radius	**1.7 m**
Aspect Ratio	**4.5**
Fusion Power	**2400 MW**
Average NWL	**2.6 MW/m^2**
Net Electric Power	**1000 MW$_e$**
COE ($2004)	**~83 mills/kWh**



* F. Najmabadi, "Overview of ARIES-CS Compact Stellarator," Plenary Session, Monday @ 3 PM.

\# J. Lyon et al., "Optimization of the ARIES-CS Compact Stellarator Power Plants Parameters," ARIES-CS Oral Session, Tuesday @ 8 AM.
L.P. Ku, "Configuration Optimization and Physics Basis of ARIES-CS," ARIES-CS Oral Session, Wednesday @ 1 PM.

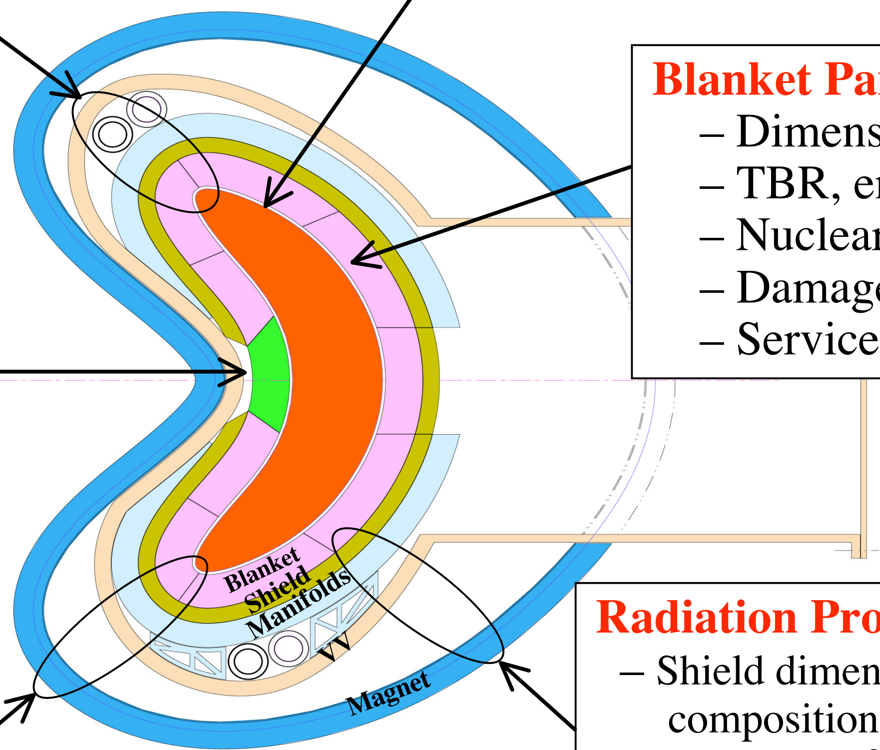
ARIES-CS Nuclear Areas of Research

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

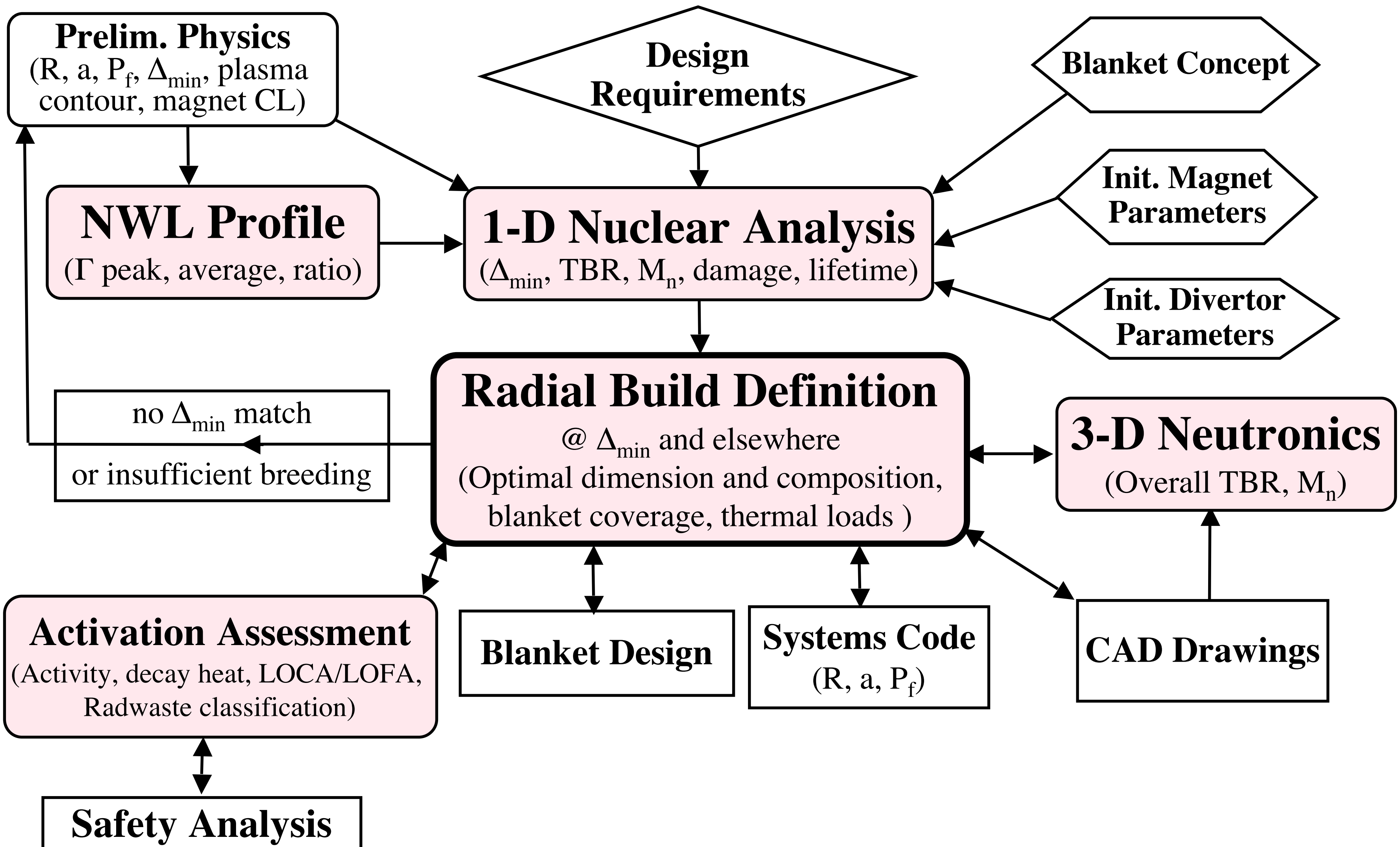
High-Performance Shielding Module at Δ_{min}



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

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

Nuclear Task Involves Active Interaction with many Disciplines



Stellarators Offer Unique Engineering Features and Challenges

- Minimum radial standoff at Δ_{min} controls machine size and cost.
  - ⇒ Well optimized radial build particularly at Δ_{min}
- Sizable components with low shielding performance (such as He manifolds) should be avoided at Δ_{min}.
- Could design tolerate non-uniform blanket/shield at Δ_{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 MCNP neutronics code.
- Economics and safety constraints control design of all components from beginning.

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

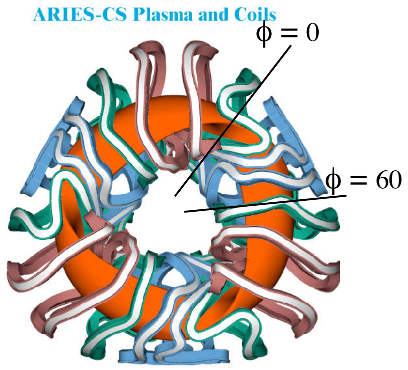
Breeder	Multiplier	Structure	FW/Blanket Coolant	Shield Coolant	VV Coolant
Internal VV@:					
Flibe	Be	FS	Flibe	Flibe	H_2O
LiPb (backup)	–	SiC	**LiPb**	**LiPb**	H_2O
LiPb (reference)	**–**	**FS**	**He/LiPb**	**He**	H_2O
Li_4SiO_4	Be	FS	He	He	H_2O
External VV#:					
LiPb	–	FS	He/LiPb	He or H_2O	He
Li	–	FS	He/Li	He	He

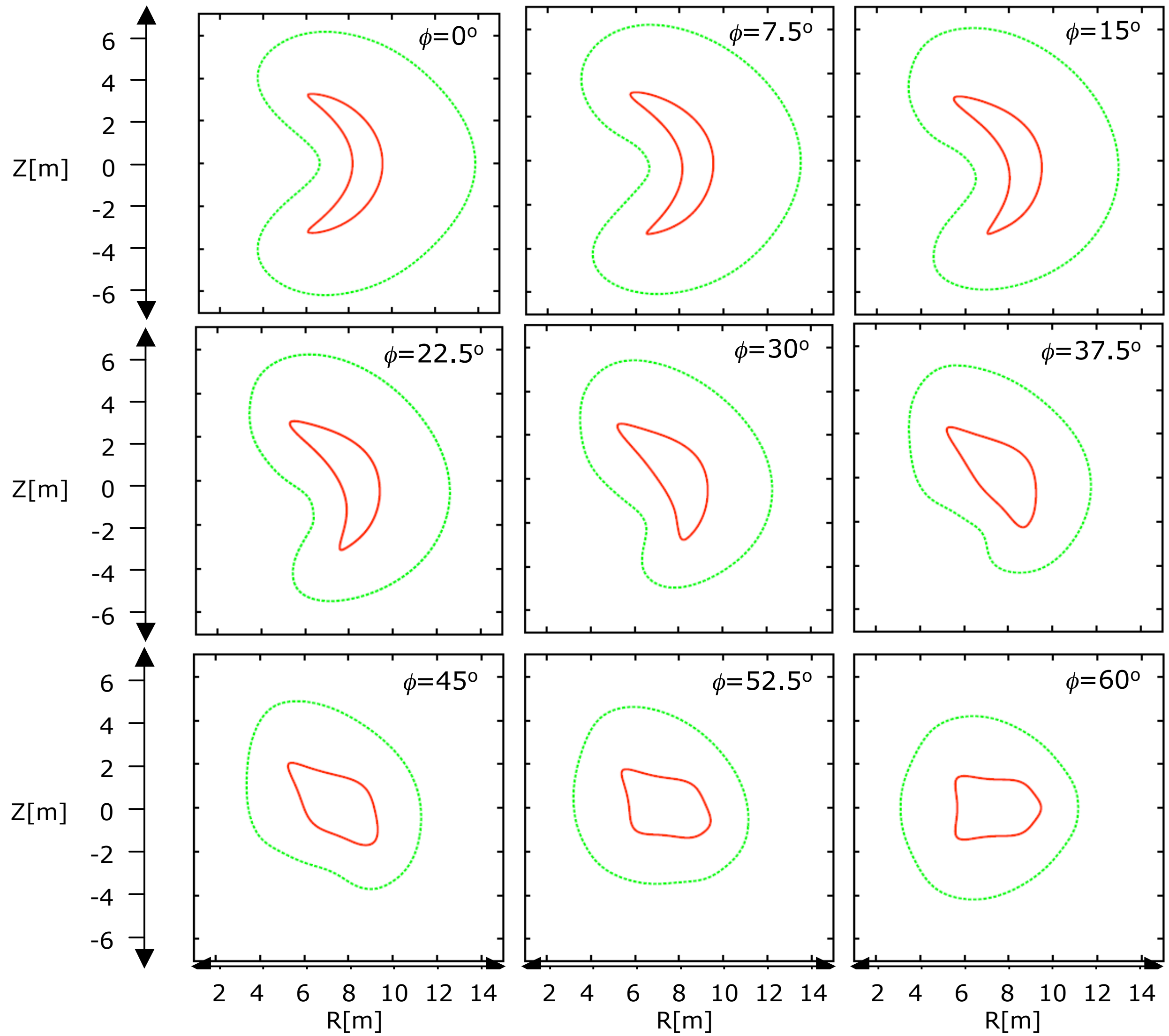
* R. Raffray, L. El-Guebaly et al., "Engineering Design and Analysis of the ARIES-CS Power Plant," ARIES-CS Oral Session, Tuesday @ 8 AM.
@ VV inside magnets.
\# VV outside magnets.

ARIES-CS Requirements Guide
In-vessel Component Design

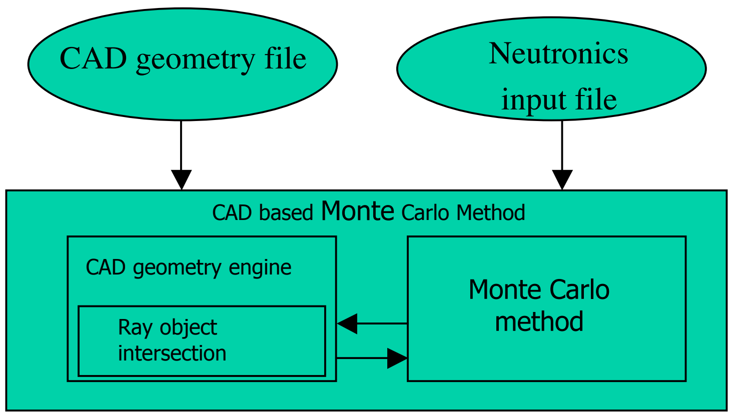
Overall TBR (for T self-sufficiency)	1.1	
Damage to Structure (for structural integrity)	200	dpa - advanced FS
Helium Production @ Manifolds and VV (for reweldability of FS)	1	He appm
S/C Magnet (@ 4 K):		
Peak Fast n **fluence** to Nb_3Sn (E_n > 0.1 MeV)	10^{19}	n/cm^2
Peak Nuclear **heating**	2	mW/cm^3
Peak **dpa** to Cu stabilizer	6×10^{-3}	dpa
Peak **Dose** to electric insulator	$> 10^{11}$	rads
Plant Lifetime	40	FPY
Availability	85%	
Operational dose to workers and public	< 2.5	mrem/h

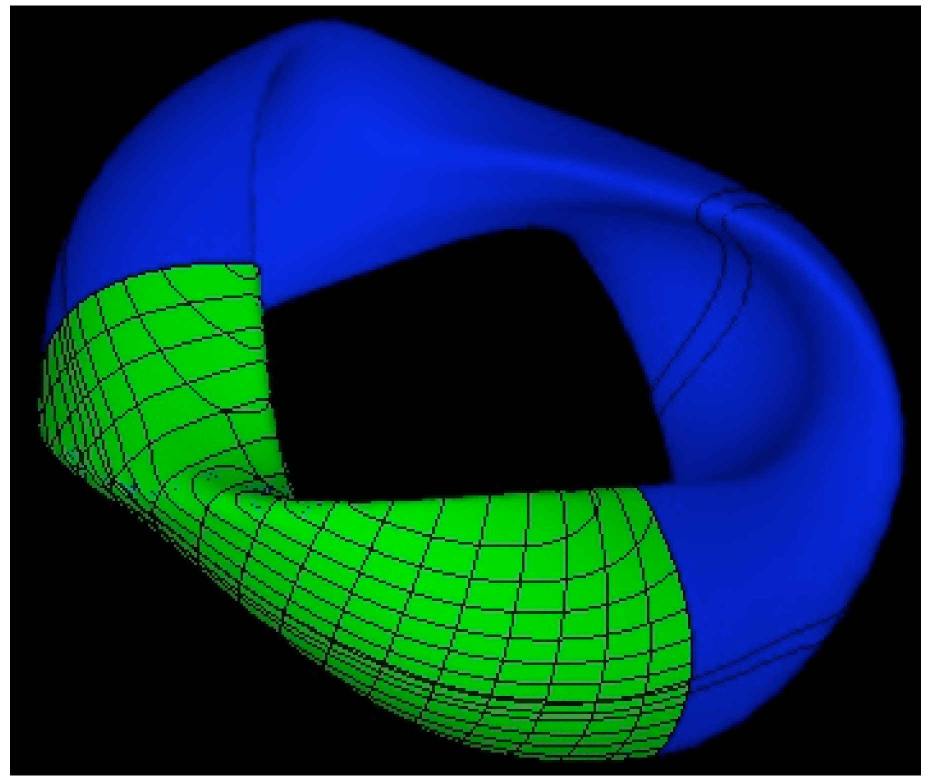
FW Shape Varies Toroidally and Poloidally: Challenging 3-D Modeling Problem





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

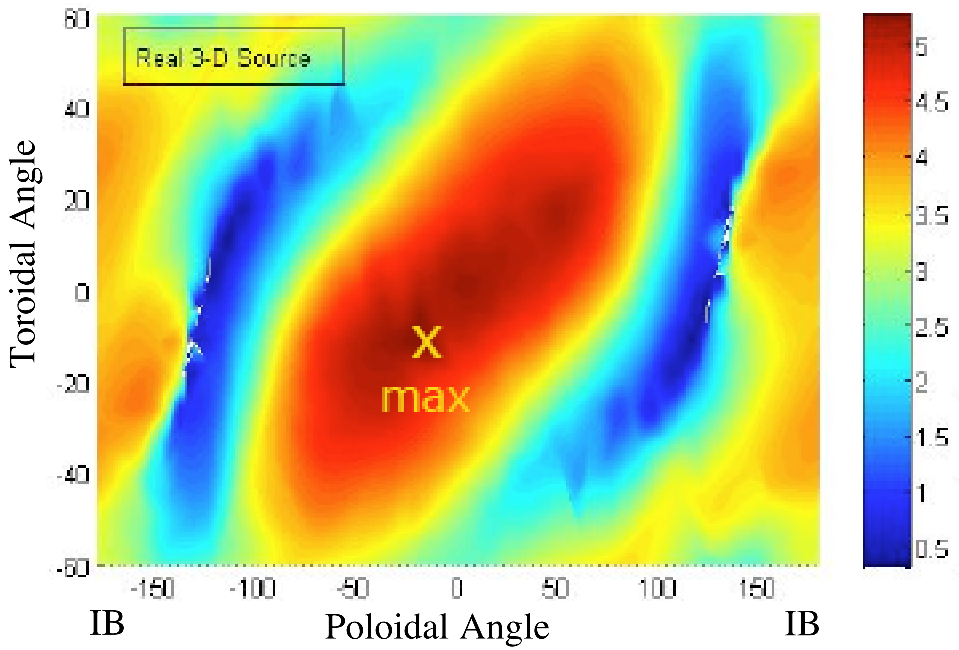


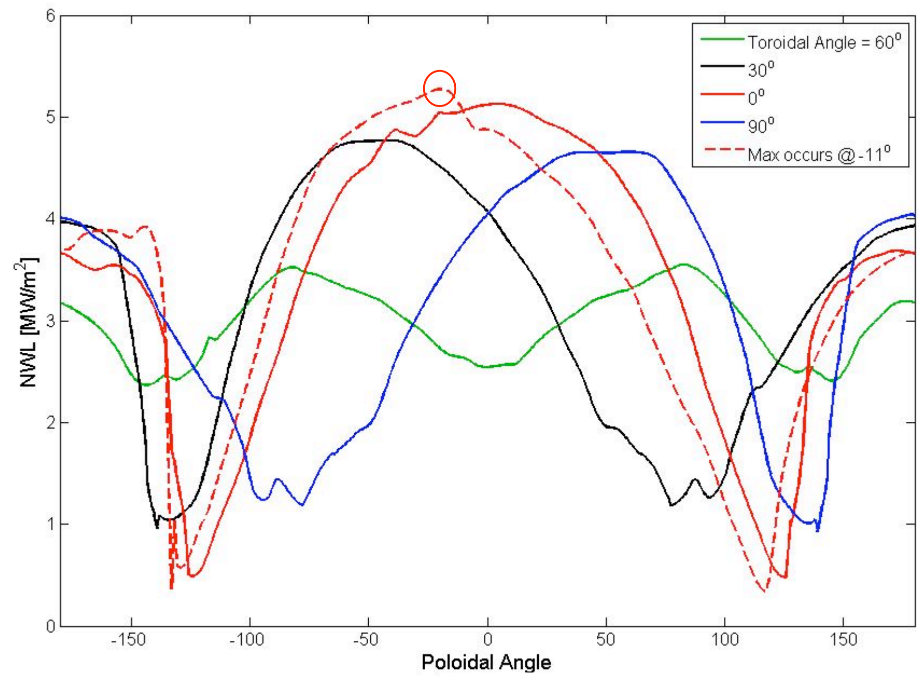


- Only viable approach for ARIES-CS 3-D neutronics modeling*.
- Geometry and ray tracing in CAD; radiation transport physics in MCNPX.

* P. Wilson, T. Tautges, M. Sawan, L. El-Guebaly, D. Henderson, G. Sviatoslavsky, B. Kiedrowski, A. Ibrahim, "Innovations in 3-Dimensional Neutronics Analysis for Fusion Systems," Computational Tools and Validation Experiments Session - Tuesday at 3 PM.

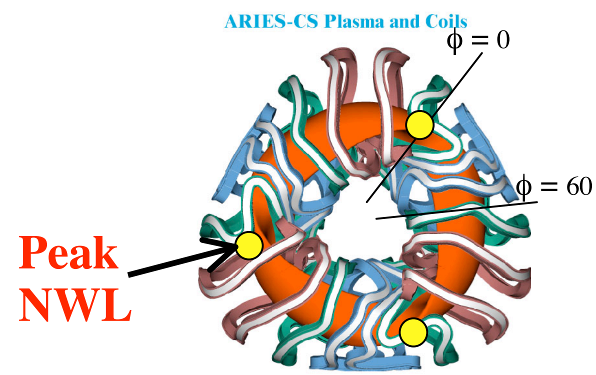
Neutron Wall Loading Distribution*





	Peak (Min) [MW/m²]	Toroidal Angle (degrees)	Poloidal Angle (degrees)
	5.26 (0.32)	-11 (-4)	-18 (-116)

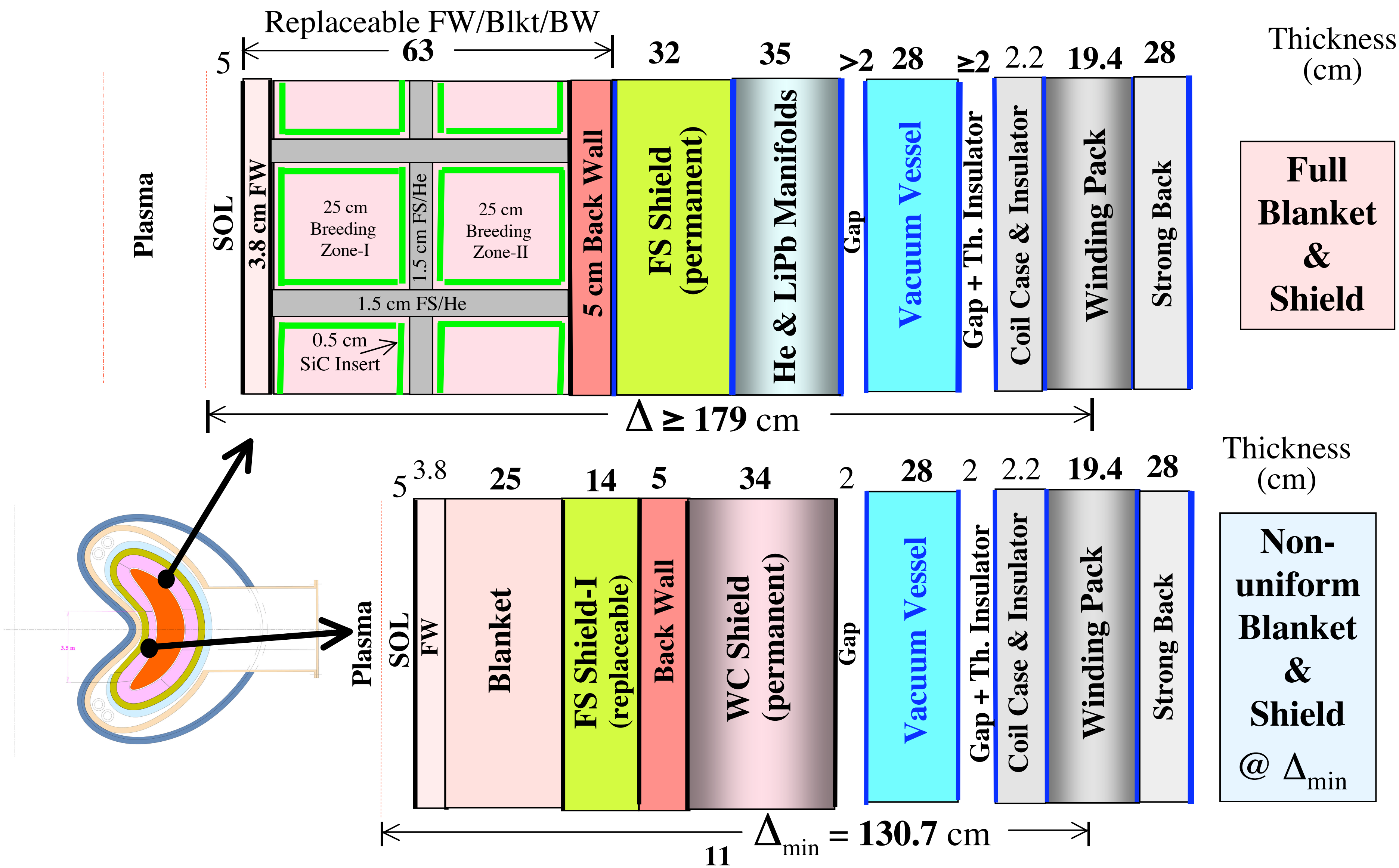
Peak/Ave. NWL = 2



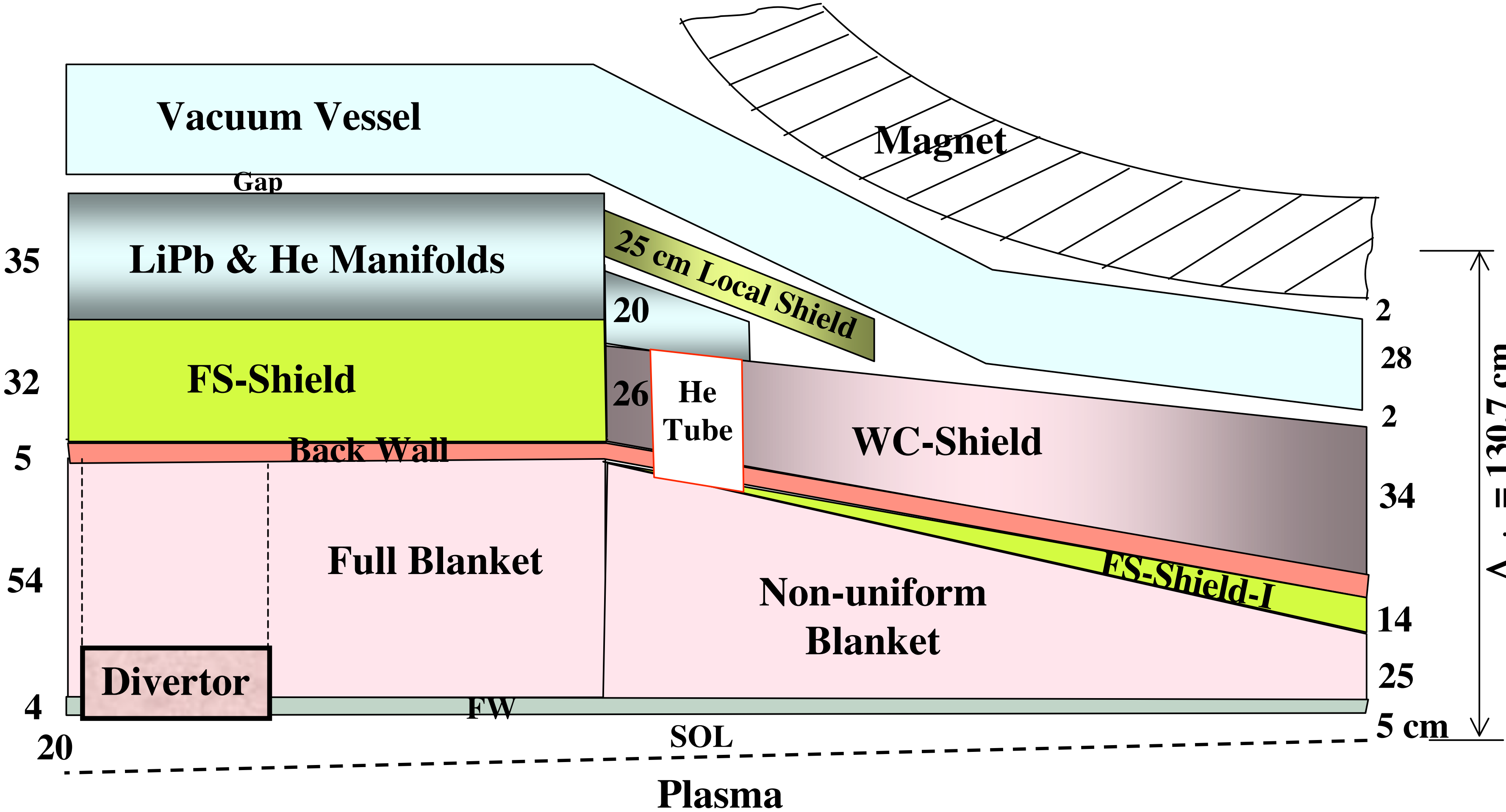
* P. Wilson, B. Kiedrowski, L. El-Guebaly, T. Tautges, G. Sviatoslavsky, J. Lyon, and X. Wang, "Three-Dimensional Neutronics Analysis of ARIES-CS Using CAD-based Tools," ARIES-CS Oral Session - Tuesday at 8 AM.

Well-Optimized Blanket & Shield Protect Vital Components

(5.3 MW/m² Peak Γ)



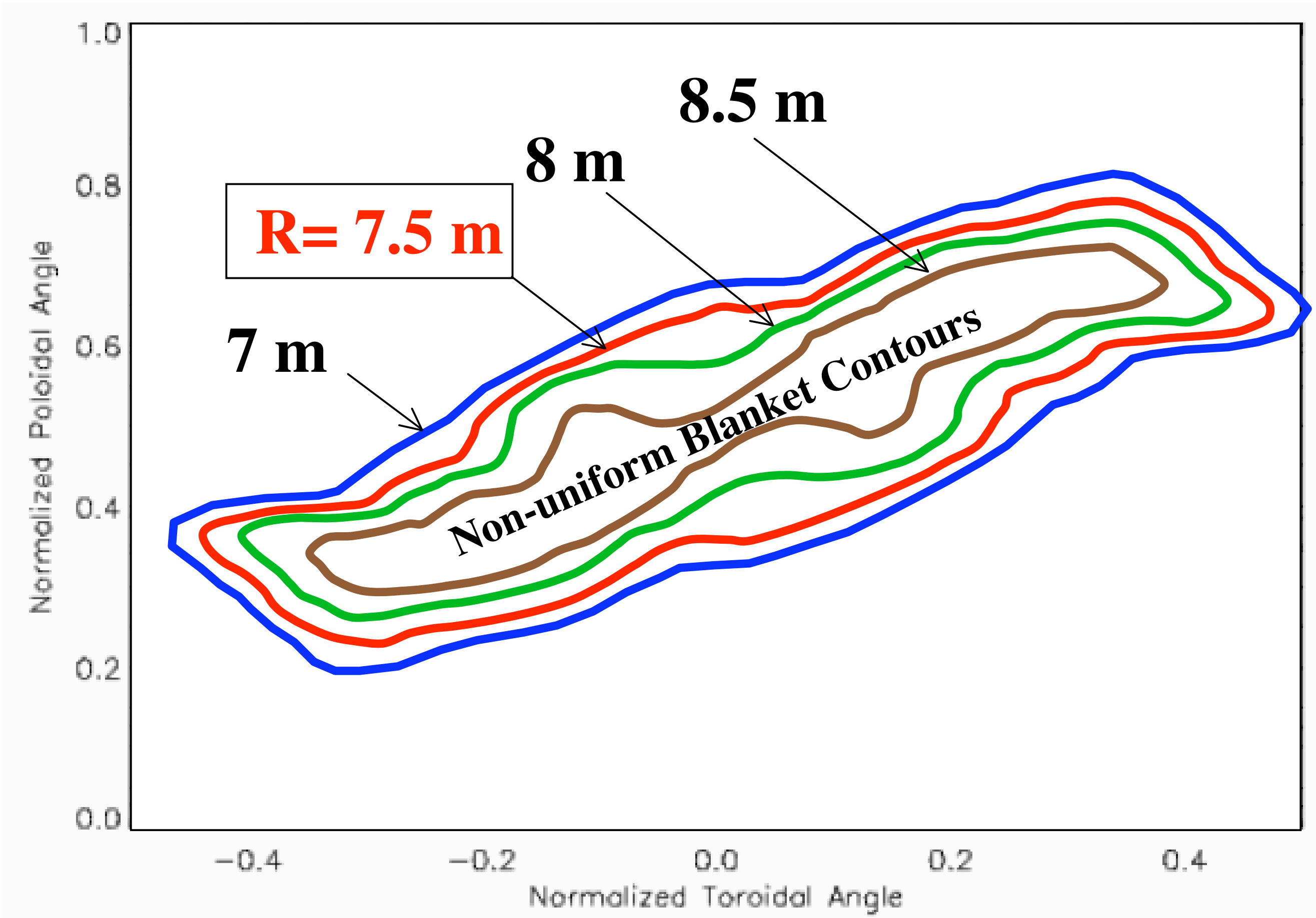
High Performance Components at Δ_{min} Help Achieve Compactness, Minimize Major Radius, and Enhance Economics



Full Blanket/Shield **and** Divertor (61%+15%= 76% of FW area)

Non-uniform, Tapered Blanket/Shield (24% of FW area)

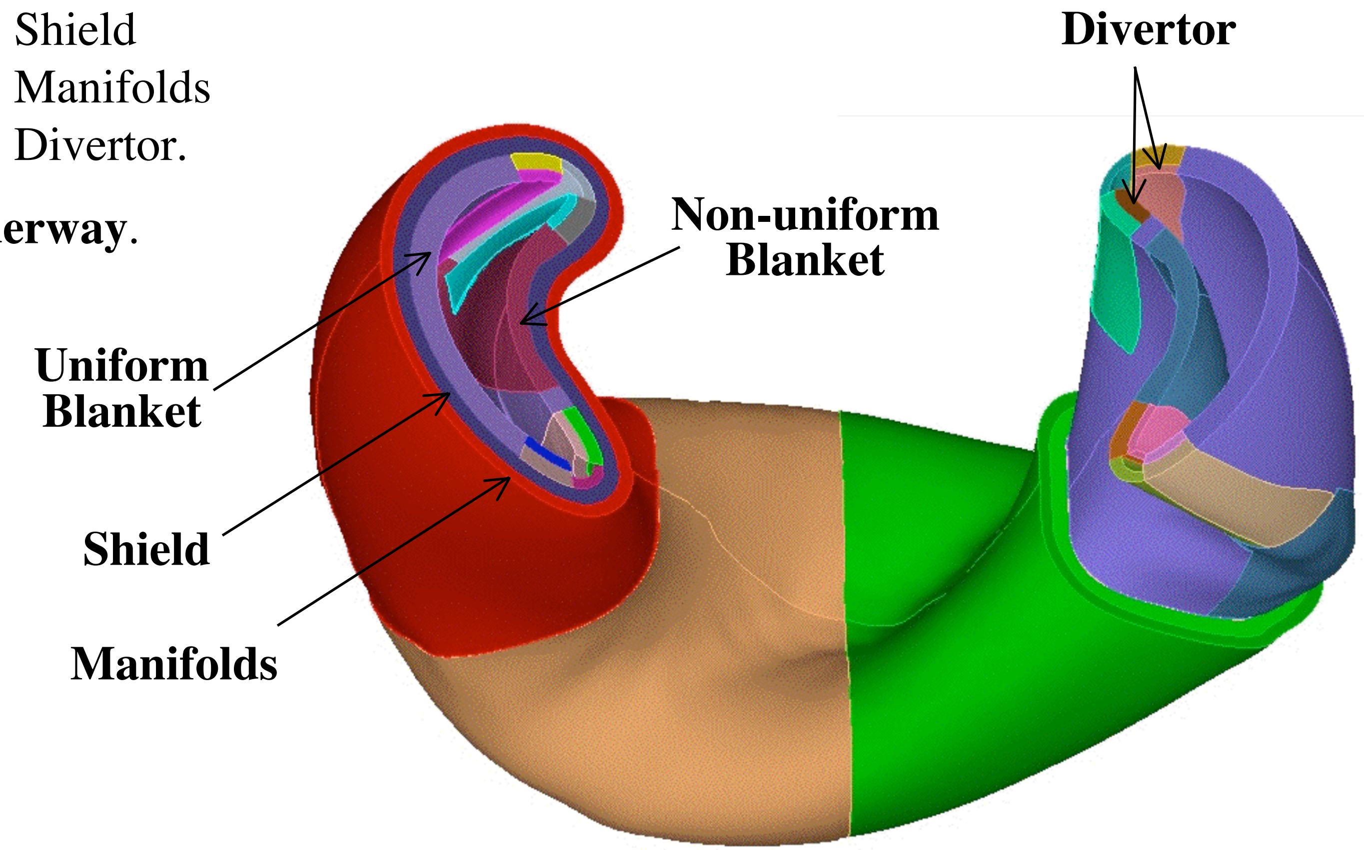
Tritium Breeding Requirement Determined Minimum Major Radius



- Large machines breed more T as non-uniform blanket coverage decreases with R.
- Designs with R < 7.5 m will not provide T self-sufficiency.

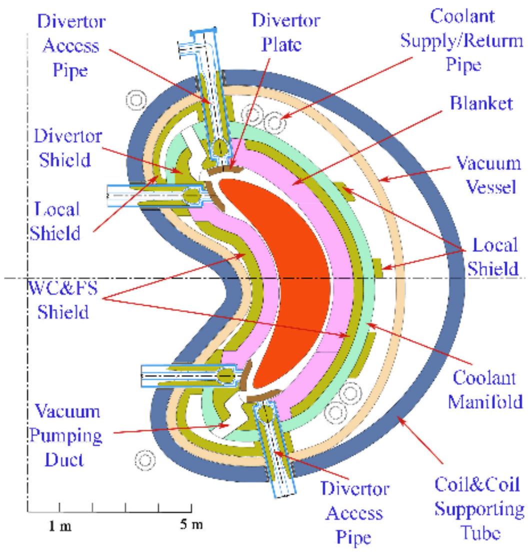
Reference Blanket Breeds Sufficient Tritium for R = 7.75 m Machine

- Overall **TBR slightly exceeds 1.1** based on 1-D estimate
- **3-D model** includes essential components for TBR:
  - Non-uniform and full blanket/shield
  - Homogenized: FW/Blanket/BW
    Shield
    Manifolds
    Divertor.
- **3-D analysis is underway**.

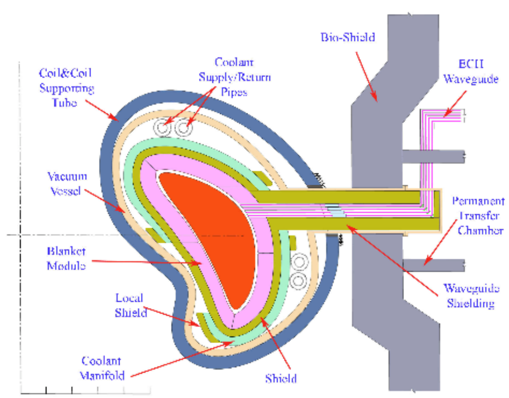


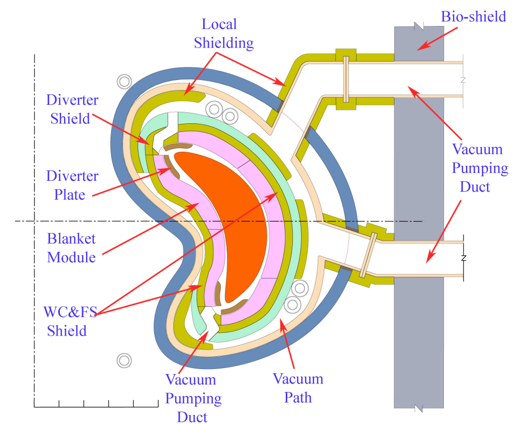
Neutron Streaming Through Penetrations Compromises Shielding Performance

- **7 types of penetrations**:
  - 198 He tubes for blanket (32 cm ID)
  - **24 Divertor He access pipes (30-60 cm ID)**
  - 30 Divertor pumping ducts (42 x 120 cm each)
  - 12 Large pumping ducts (1 x 1.25 m each)
  - 3 ECH ducts (24 x 54 cm each).
  - 6 main He pipes - HX to/from blanket (72 cm ID each)
  - 6 main He pipes - HX to/from divertor (70 cm ID each)



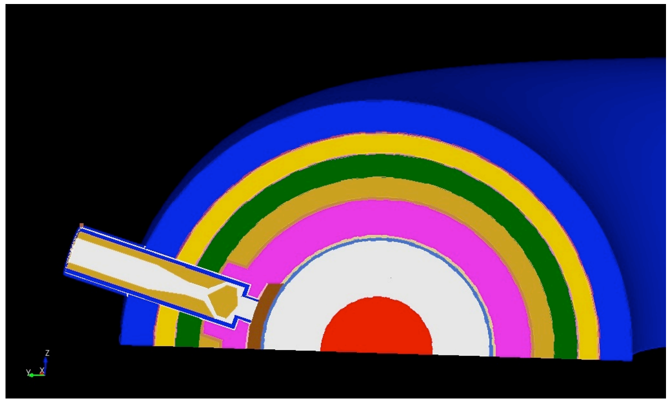
- **Potential solutions**:
  - Local shield behind penetrations
  - He tube axis oriented toward lower neutron source
  - Penetration shield surrounding ducts
  - Replaceable shield close to penetrations
  - Avoid rewelding VV and manifolds close to penetrations
  - Bends included in some penetrations.

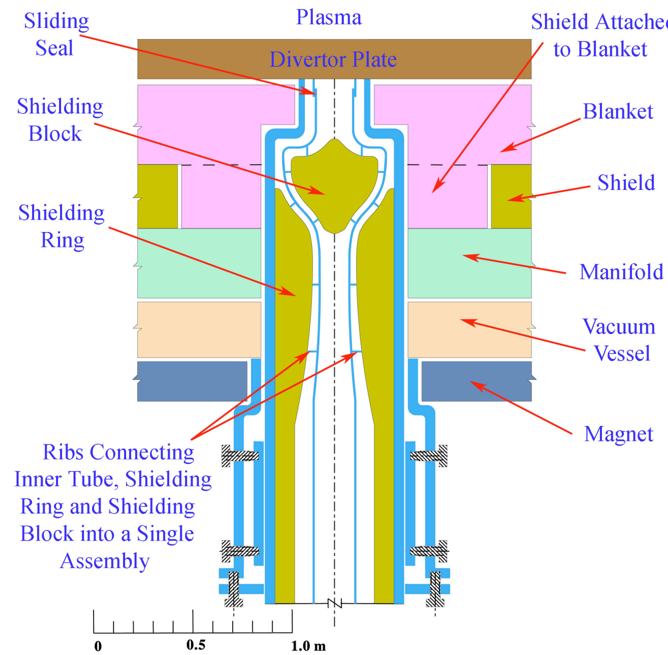




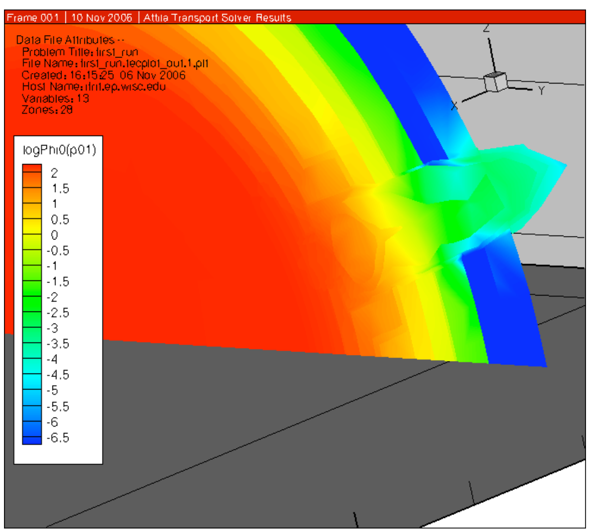
3-D Assessment of Streaming Through Divertor He Access Pipe

ATTILA 3-D Model





Neutron Flux Distribution



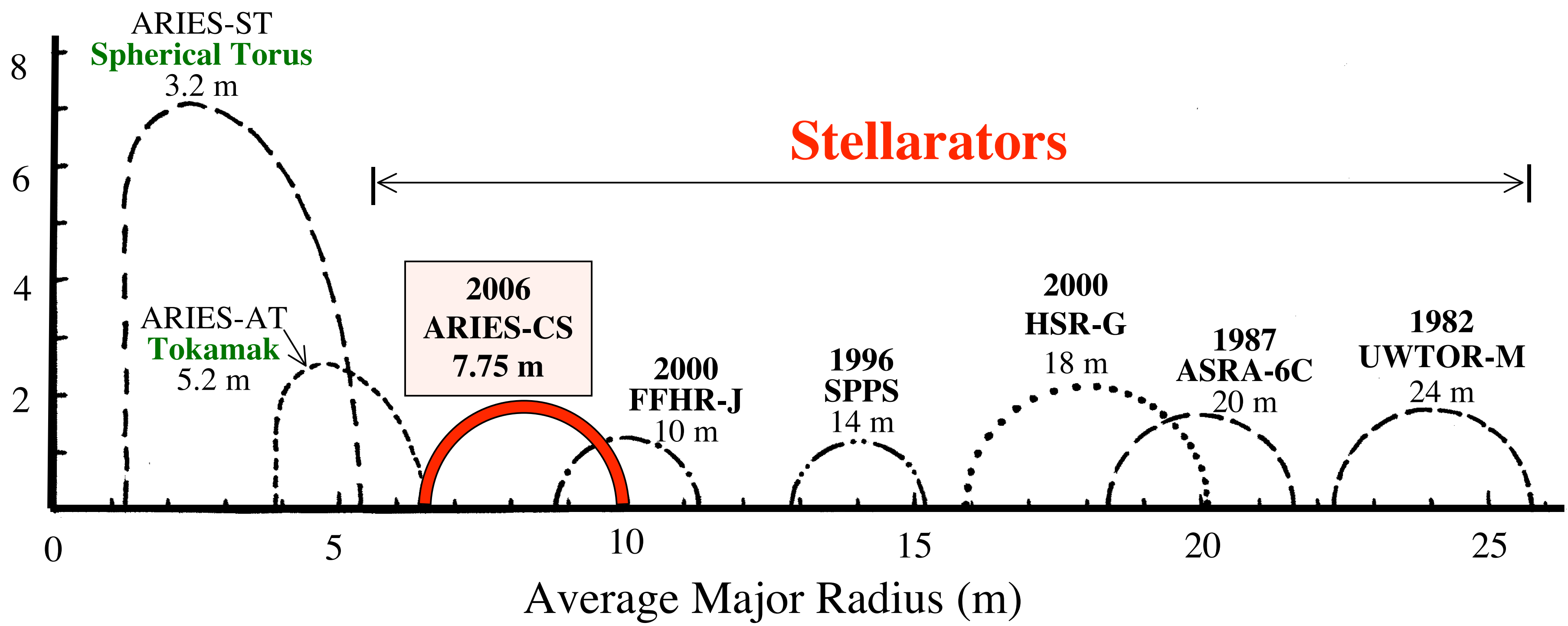
Ongoing analysis will confirm protection of surrounding components

Key Nuclear Parameters

Peak NWL	**5.3 MW/m^2**
Average NWL	**2.6 MW/m^2**
Peak to Average NWL	**2**
Overall TBR	**~ 1.1***
FW/blanket Lifetime	**3 FPY**
Shield/manifold/VV/magnet Lifetime	**40 FPY**
Overall Energy Multiplication	**1.16***
Δ_{min}	**1.3 m**
Δ_{max}	**1.8 m**

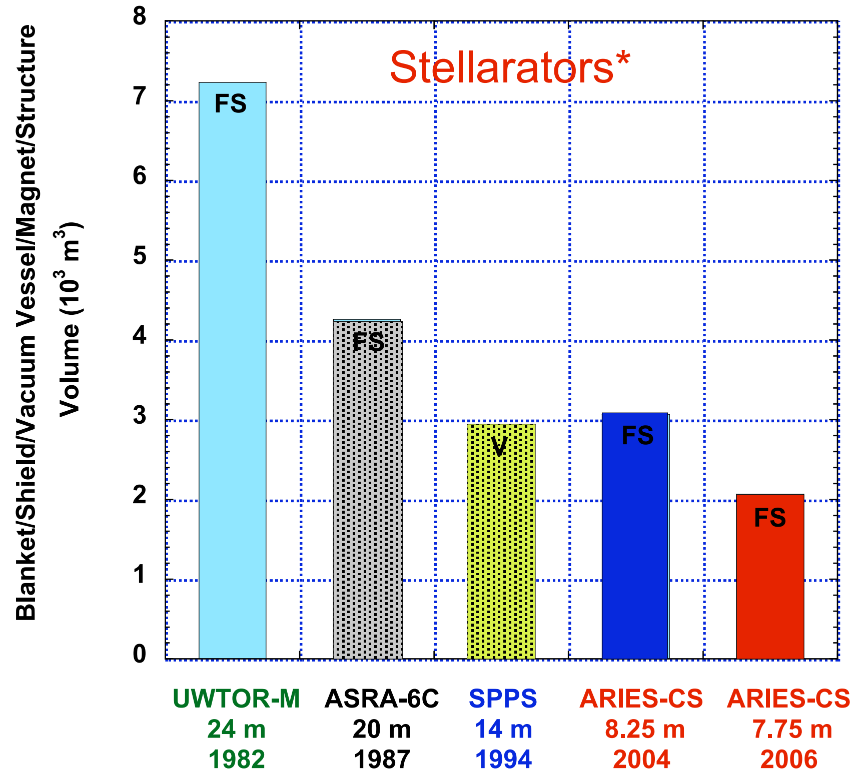
* To be confirmed with ongoing 3-D analysis.

ARIES-CS Major Radius Approaches R of Advanced Tokamaks



Well optimized radial build along with advanced physics helps reduce ARIES-CS size

ARIES Project Committed to Waste Minimization

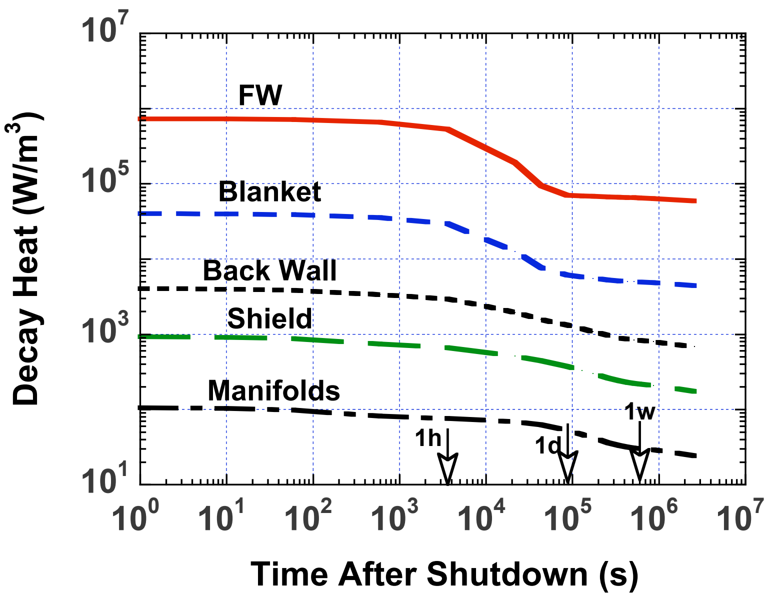


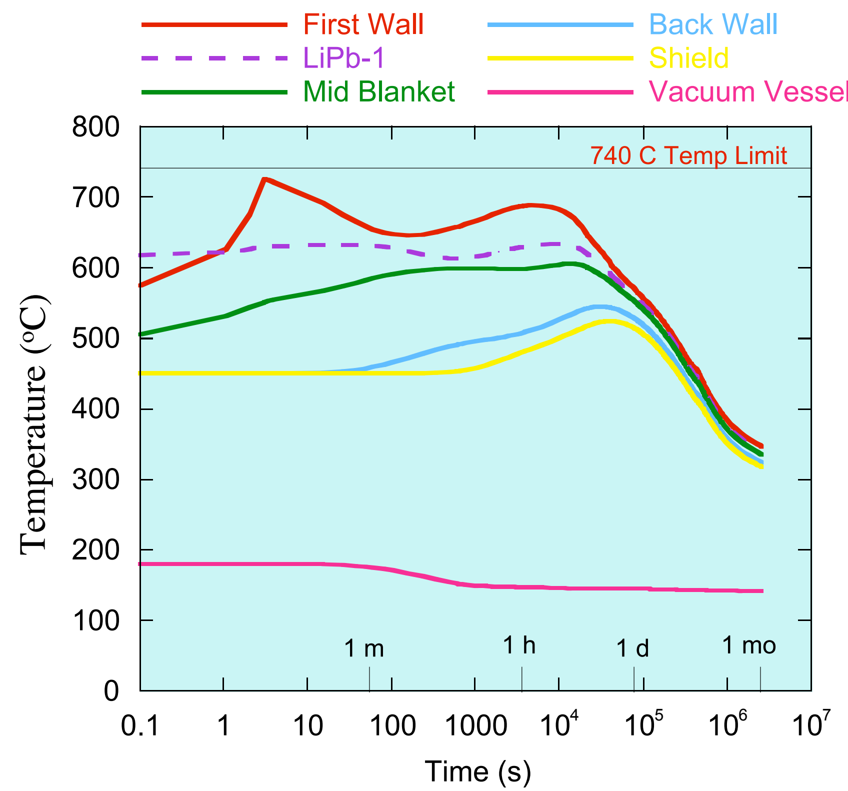
Stellarator waste volume dropped by factor of 3 over 25 y study period

* Actual volumes (not compacted, no replacements).

Activation and Environmental Issues

In-vessel Components Exhibit Structural Integrity during LOCA/LOFA Event*

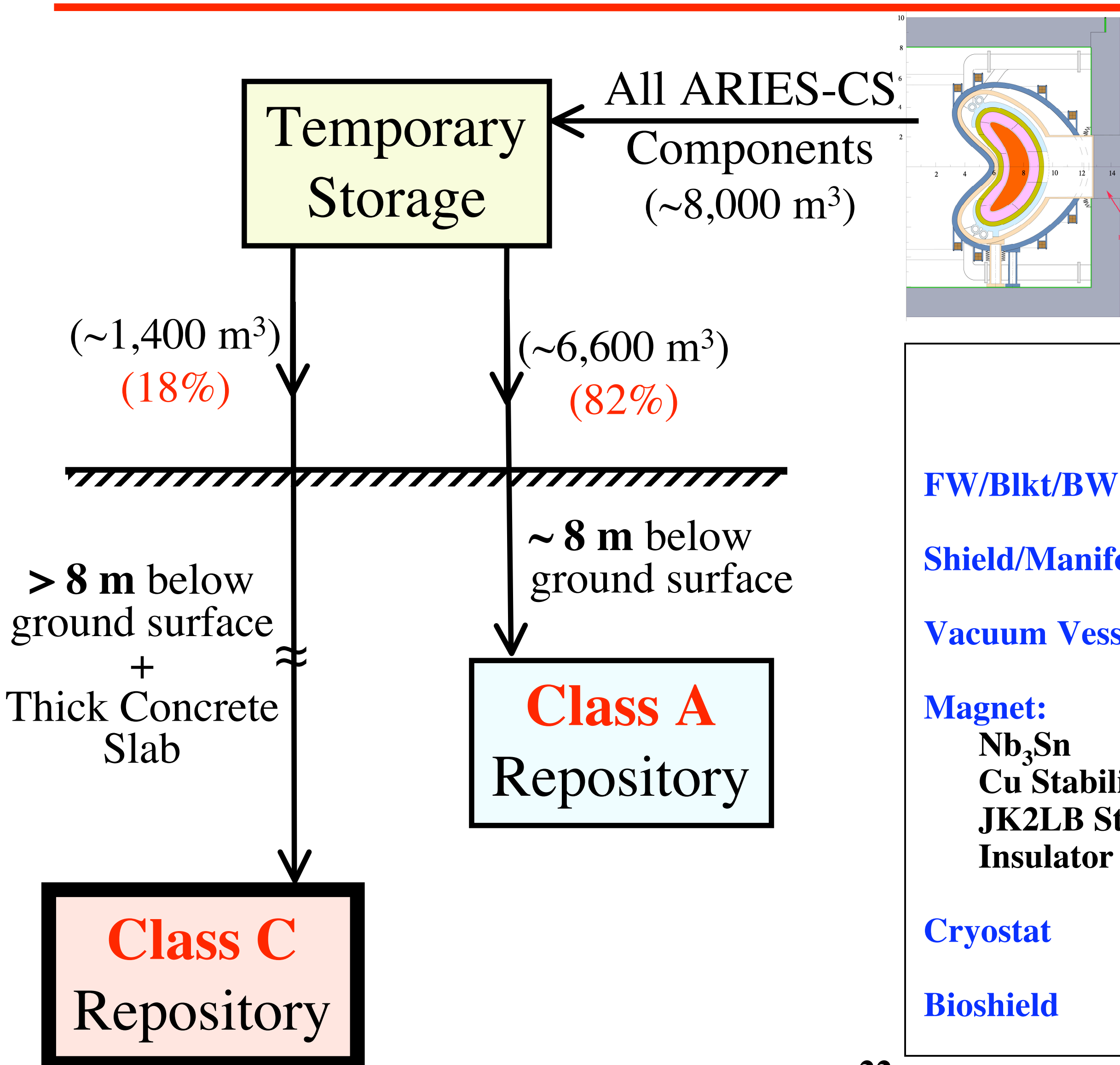




- Design Base Accident scenario: He LOCA and LiPb LOFA in **all** modules and water LOFA in VV.
- Plasma stays on for 3 seconds after onset of LOCA/LOFA.
- Peak temperature remains below 740°C – reusability limit for ferritic steel.

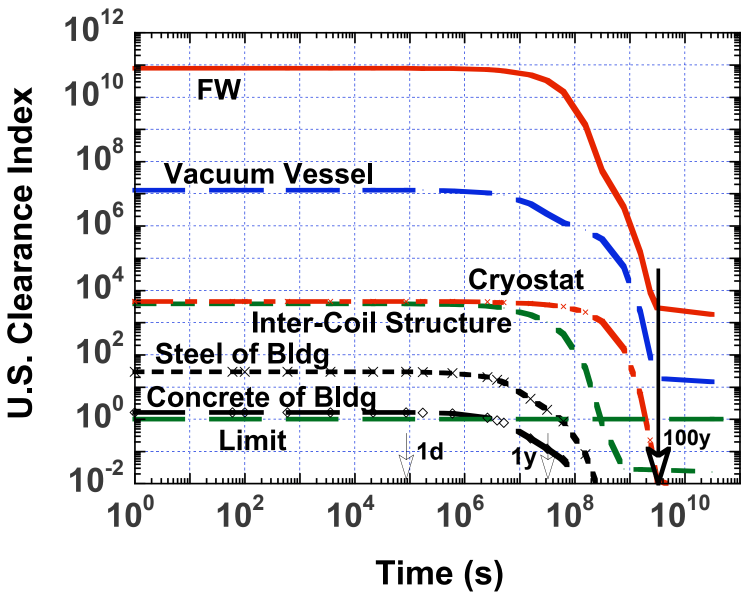
* C. Martin and L. El-Guebaly, "ARIES-CS Loss of Coolant and Loss of Flow Accident Analyses," ARIES-CS Oral Session - Tuesday at 8 AM.

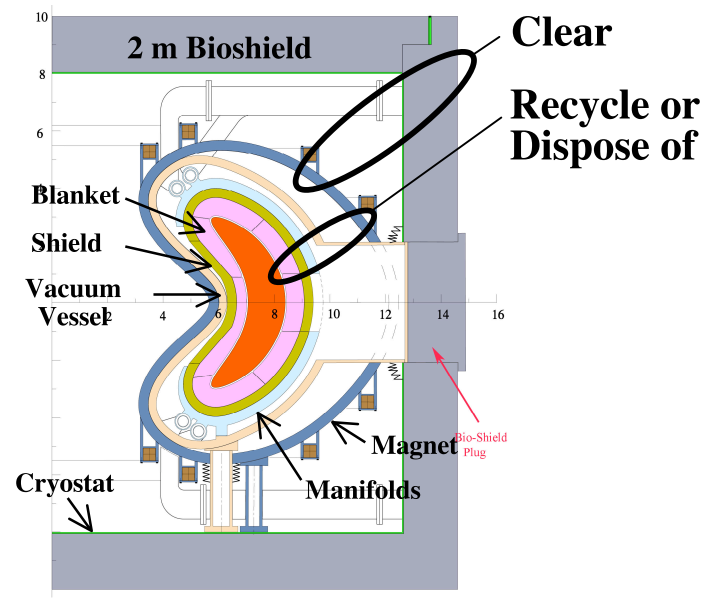
ARIES-CS Generates Only Low-Level Waste

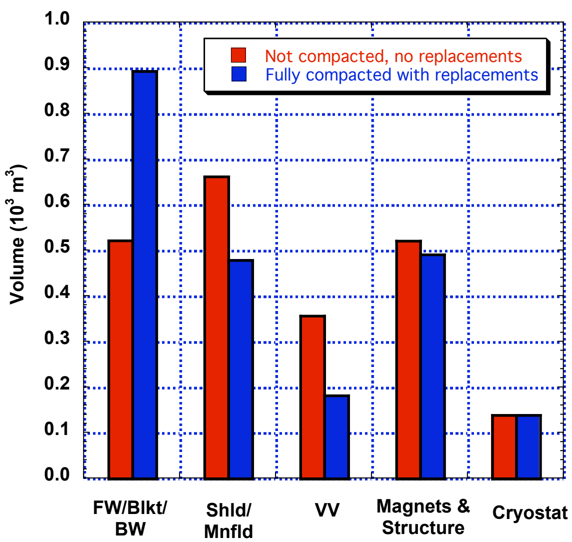


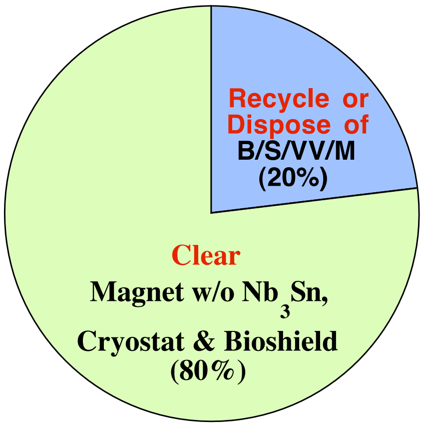
	Class C LLW	Class A LLW	Could be Cleared?
FW/Blkt/BW	√		no
Shield/Manifolds	√		no
Vacuum Vessel		√	no
Magnet:			
Nb_3Sn	√		no
Cu Stabilizer		√	√
JK2LB Steel		√	√
Insulator		√	√
Cryostat		√	√
Bioshield		√	√

80% of ARIES-CS Active Materials can be Cleared in < 100 y after Decommission

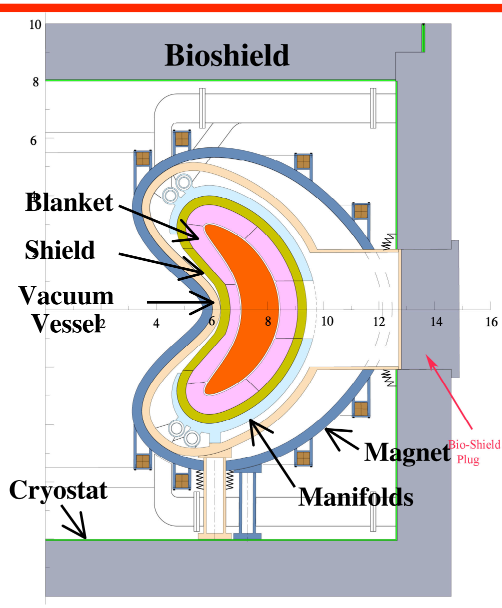


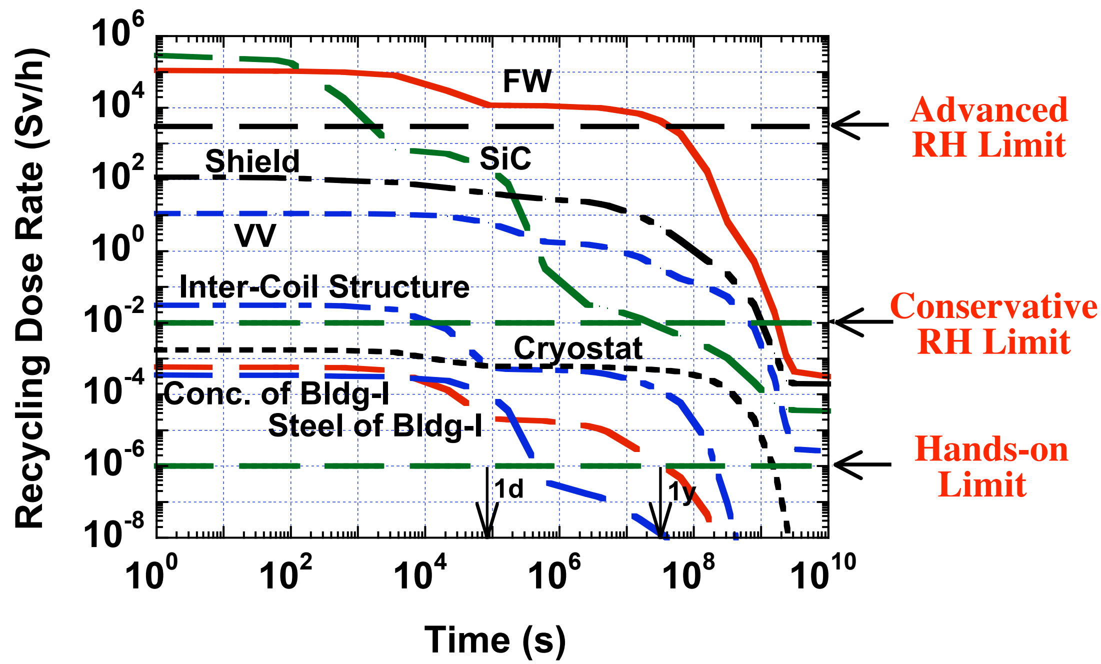






All ARIES-CS Components can be Recycled in 1-2 y Using Advanced and Conventional RH Equipment*





FS-based components:

- ^{54}Mn (from Fe) is main contributor to dose.
- Store components for few years to decay before recycling.
- After several life-cycles, advanced RH equipment could handle shield, manifolds, and VV.

SiC-based components:

- $^{58,60}Co$, ^{54}Mn, and ^{65}Zn contributors originate from impurities.
- Strict impurity control may allow hands-on recycling.

* L. El-Guebaly, "Environmental Benefits and Impacts of the Radwaste Management Approaches: Disposal, Recycling, and Clearance," Waste Management Oral Session - Radwaste Management Session, Wednesday at 10 AM.

Conclusions

- Novel approach developed for ARIES-CS helps reduce radial standoff, major radius, and overall cost by 25-30%.

- Radial build satisfies design requirements in terms of breeding sufficient tritium and shielding vital components.

- First time ever complex stellarator geometry modeled for nuclear assessment using UW newly developed CAD/MCNP coupling approach.

- **Activation and environmental assessment** indicates:
  - Structural integrity during LOCA/LOFA events ($T_{max} < 740^{o}C$)
  - In-vessel components can be recycled in few years using advanced RH equipment
  - Majority of waste (80%) can be cleared from regulatory control within 100 y
  - Substantial reduction in radwaste stream compared to previous stellarator designs.