Integration of Nuclear, Economics, and Safety Constraints in ARIES-CS Compact Stellarator

L. El-Guebaly[1],

P. Wilson[1], D. Henderson[1], T. Tautges[1], M. Sawan[1], G. Sviatoslavsky[1],
B. Kiedrowski[1], R. Slaybaugh[1], A. Ibrahim[1], M. Wang[1], C. Martin[1],
R. Raffray, S. Malang. J. Lyon, L.P. Ku, X. Wang, L. Bromberg,
B. Merrill, L. Waganer, F. Najmabadi,
and the ARIES-CS Team

[1]**Fusion Technology Institute**
University of Wisconsin - Madison
http://fti.neep.wisc.edu/UWNeutronicsCenterOfExcellence

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Stellarators Offer Unique Features and Engineering Challenges

Advantages:

- Inherently steady-state devices
- No need for large plasma current
- No external current drive
- No risk of plasma disruptions
- Low recirculating power due to absence of current-drive requirements
- No instability and positional control systems.

Challenges:

- Complex geometry
- Maintainability and component replacement
- **Highly constrained local shielding areas**
- **3-D modeling for nuclear assessment**
- **Managing large volume of active materials.**

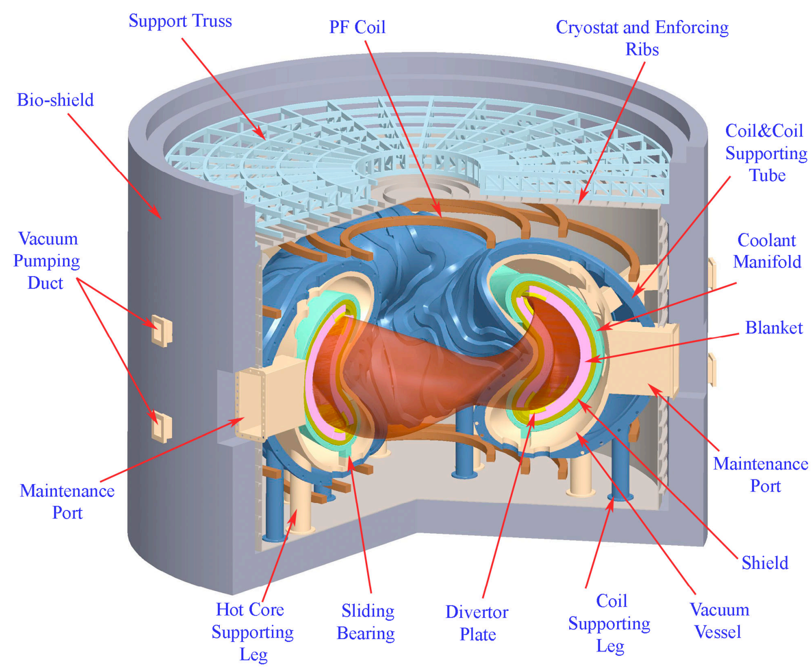
ARIES Compact Stellarator

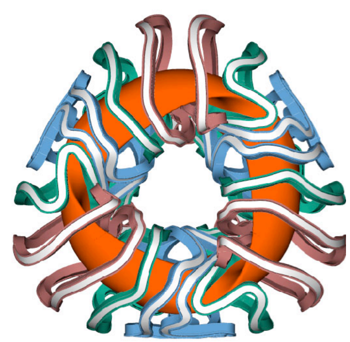
Study aimed at reducing stellarators' size by:

– Developing <u>compact</u> configuration with 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)	**78 mills/kWh**





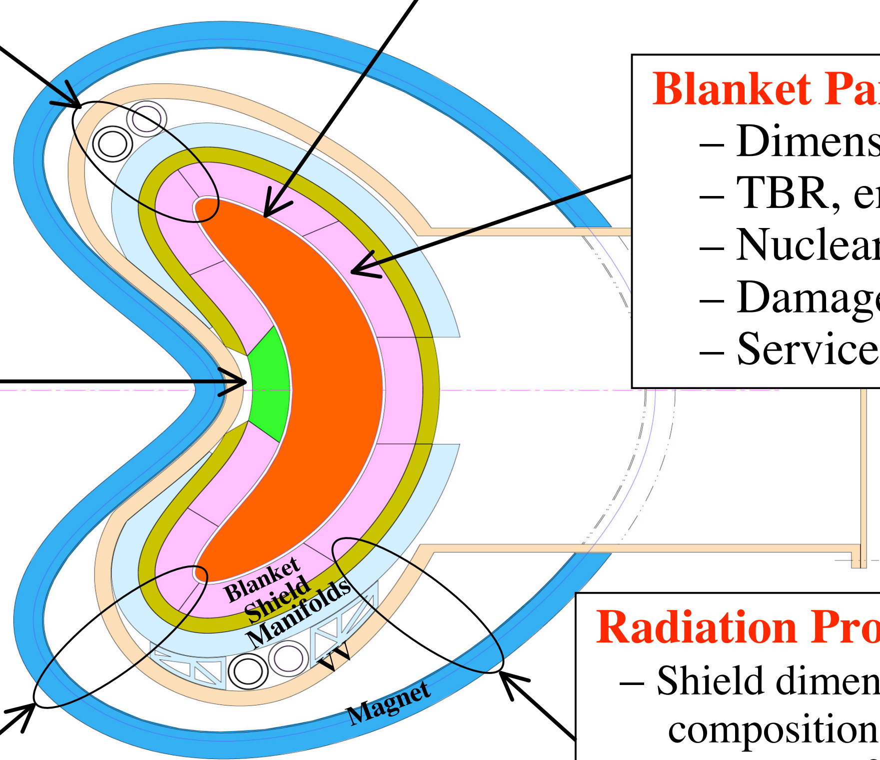
ARIES-CS Nuclear Areas of Research

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

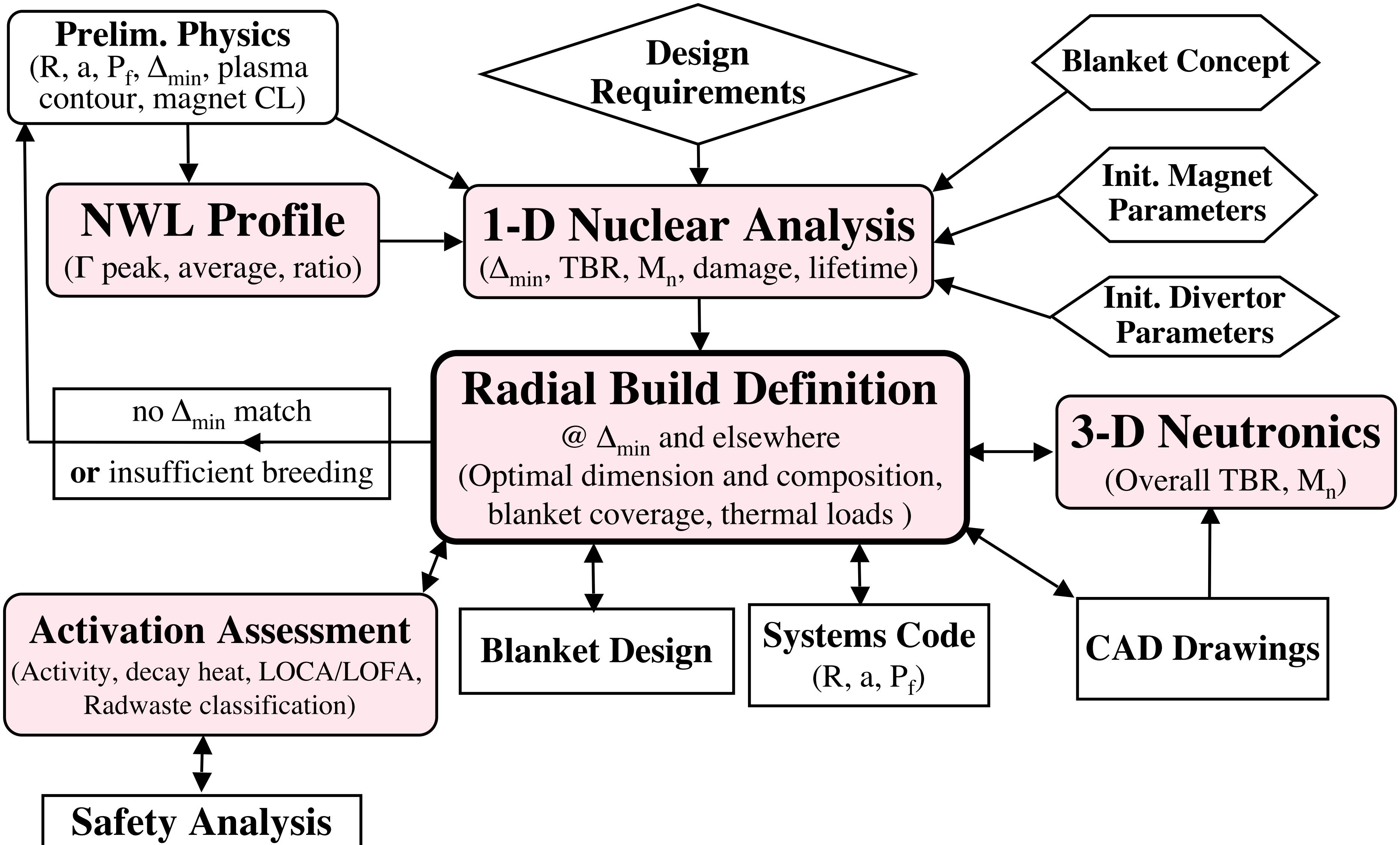
High-Performance Shielding Module at Δ_{min}



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

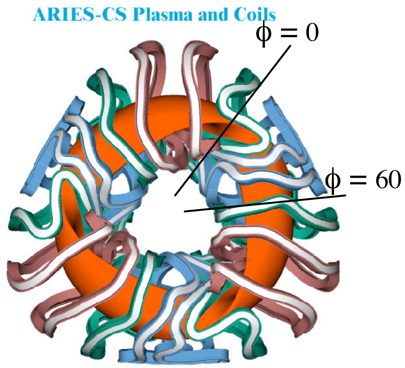


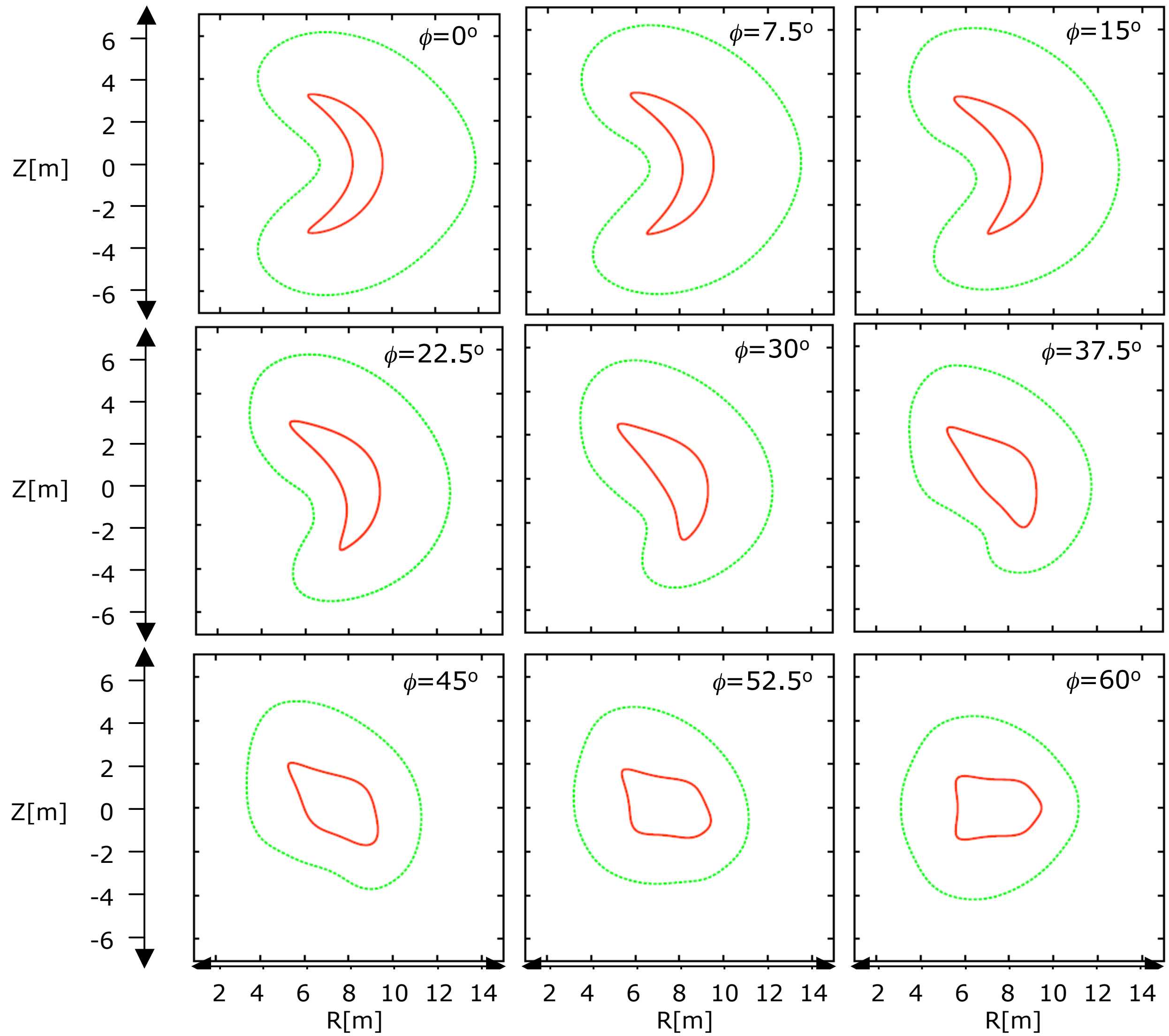
Reference Dual-cooled LiPb/FS Blanket Selected with Advanced LiPb/SiC as Backup

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

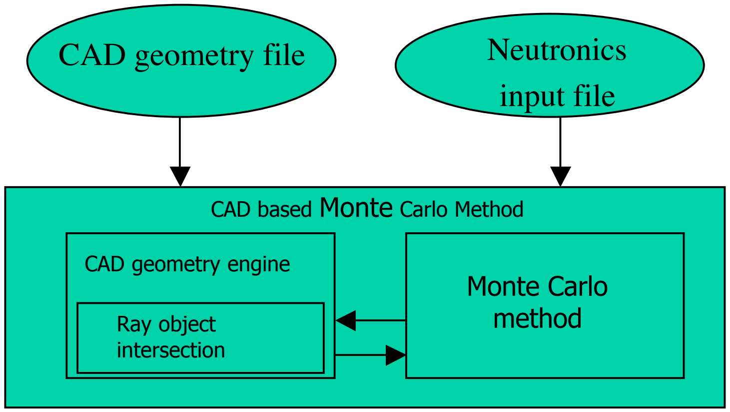
* VV inside magnets.
\# VV outside magnets.

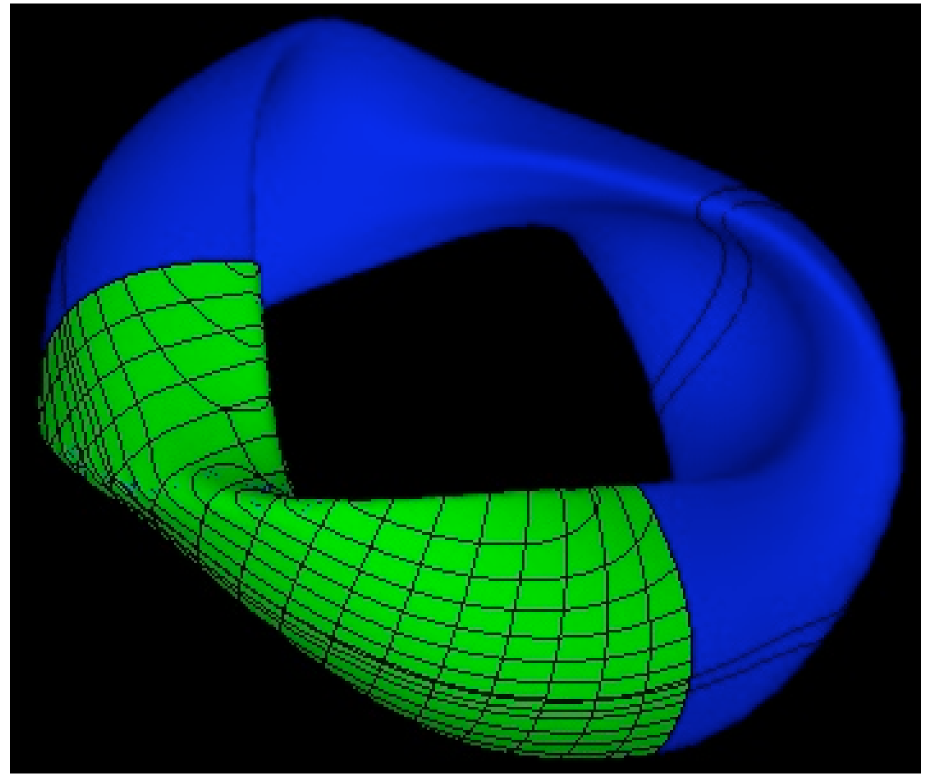
FW Shape Varies Toroidally and Poloidally: Challenging 3-D Modeling Problem





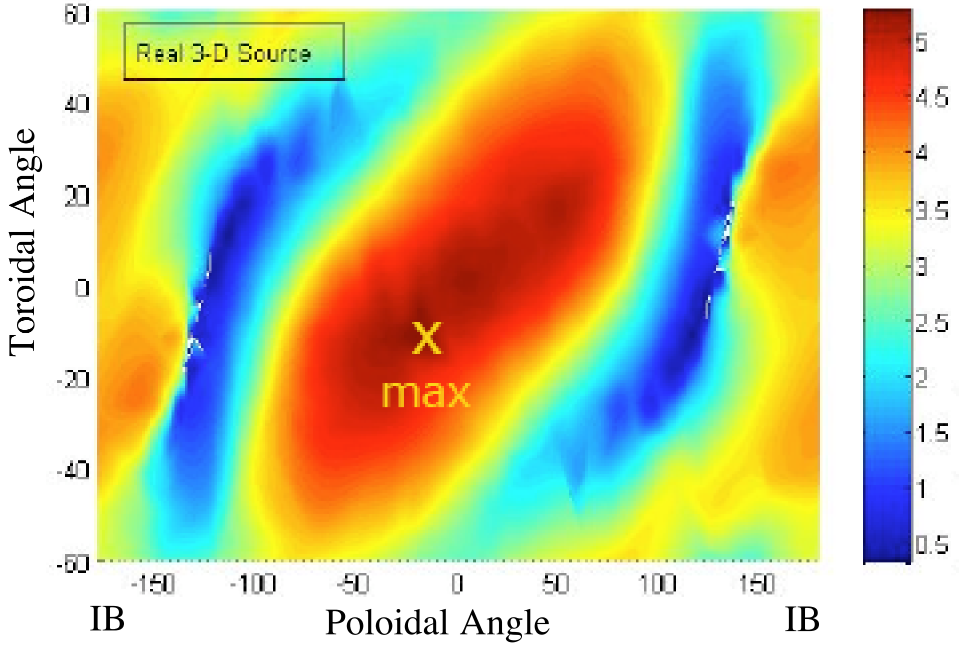
UW Developed CAD/MCNPX Coupling Approach to Model ARIES-CS for Nuclear Assessment

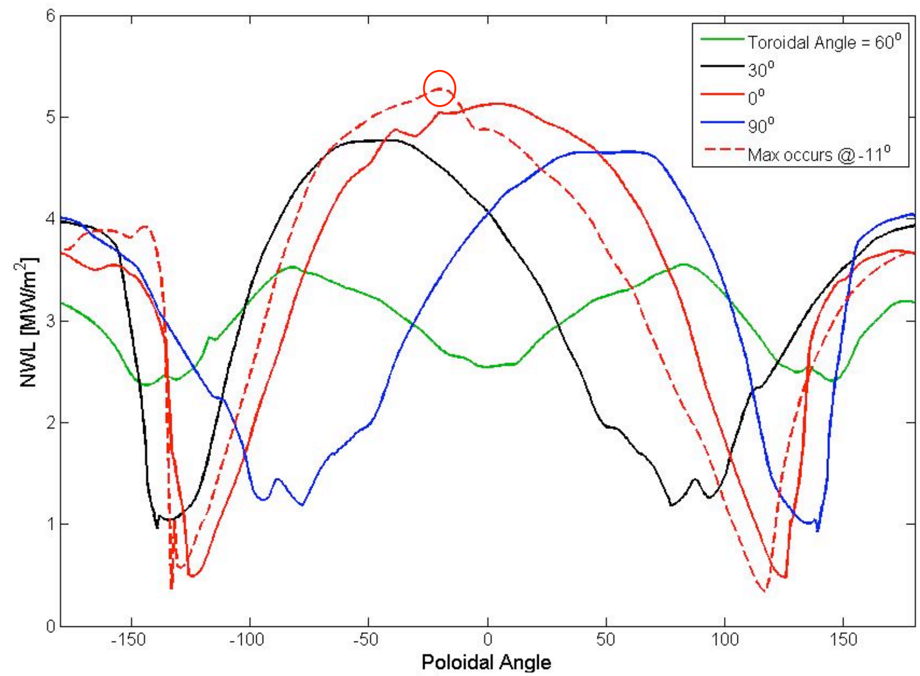




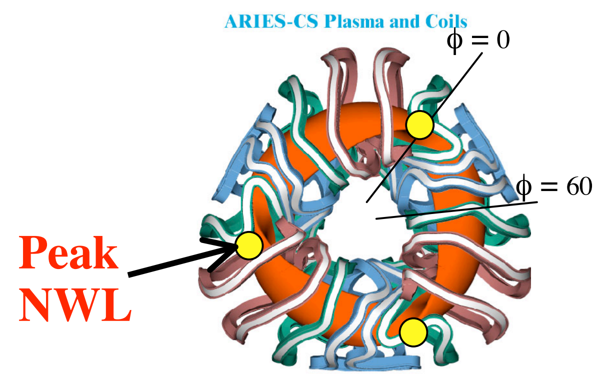
- Only viable approach for ARIES-CS 3-D neutronics modeling.
- Geometry and ray tracing in CAD
- Radiation transport physics in MCNPX code.

Neutron Wall Loading Distribution





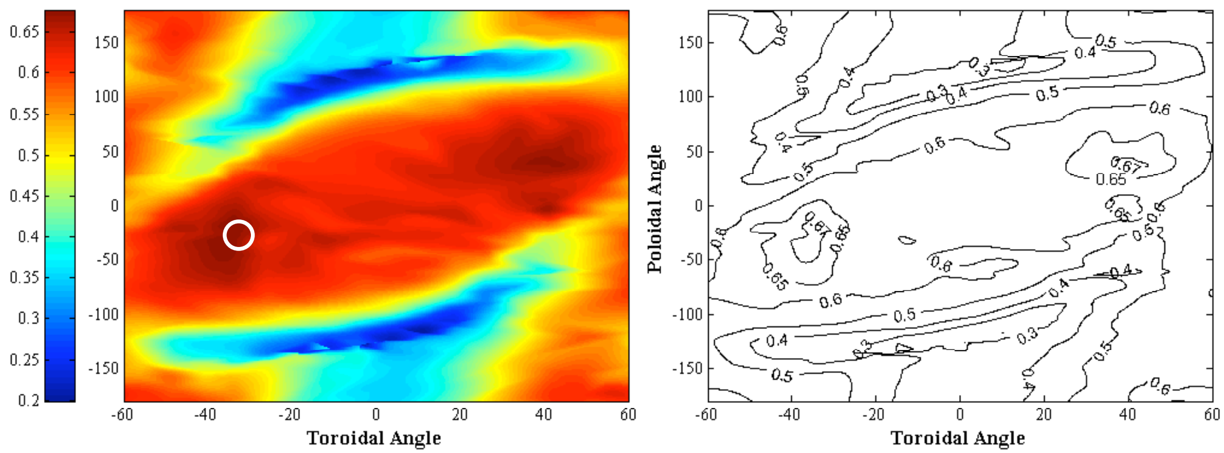
	Peak (Min) [MW/m²]	Toroidal Angle (degrees)	Poloidal Angle (degrees)
	5.26 (0.32)	-11 (-4)	-18 (-116)



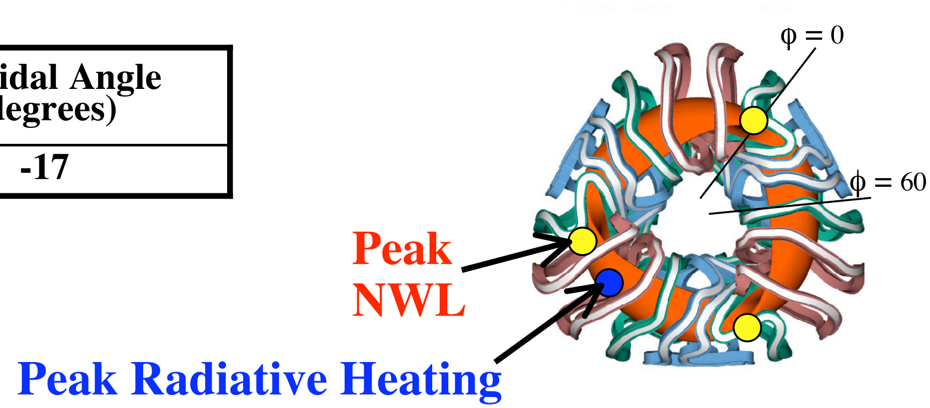
Peak/Ave. NWL = 2

Core Radiation Distribution at FW

(354 MW Bremsstrahlung radiation)



	Peak/Ave. [MW/m²]	Toroidal Angle (degrees)	Poloidal Angle (degrees)
	0.68 / 0.48	-34	-17

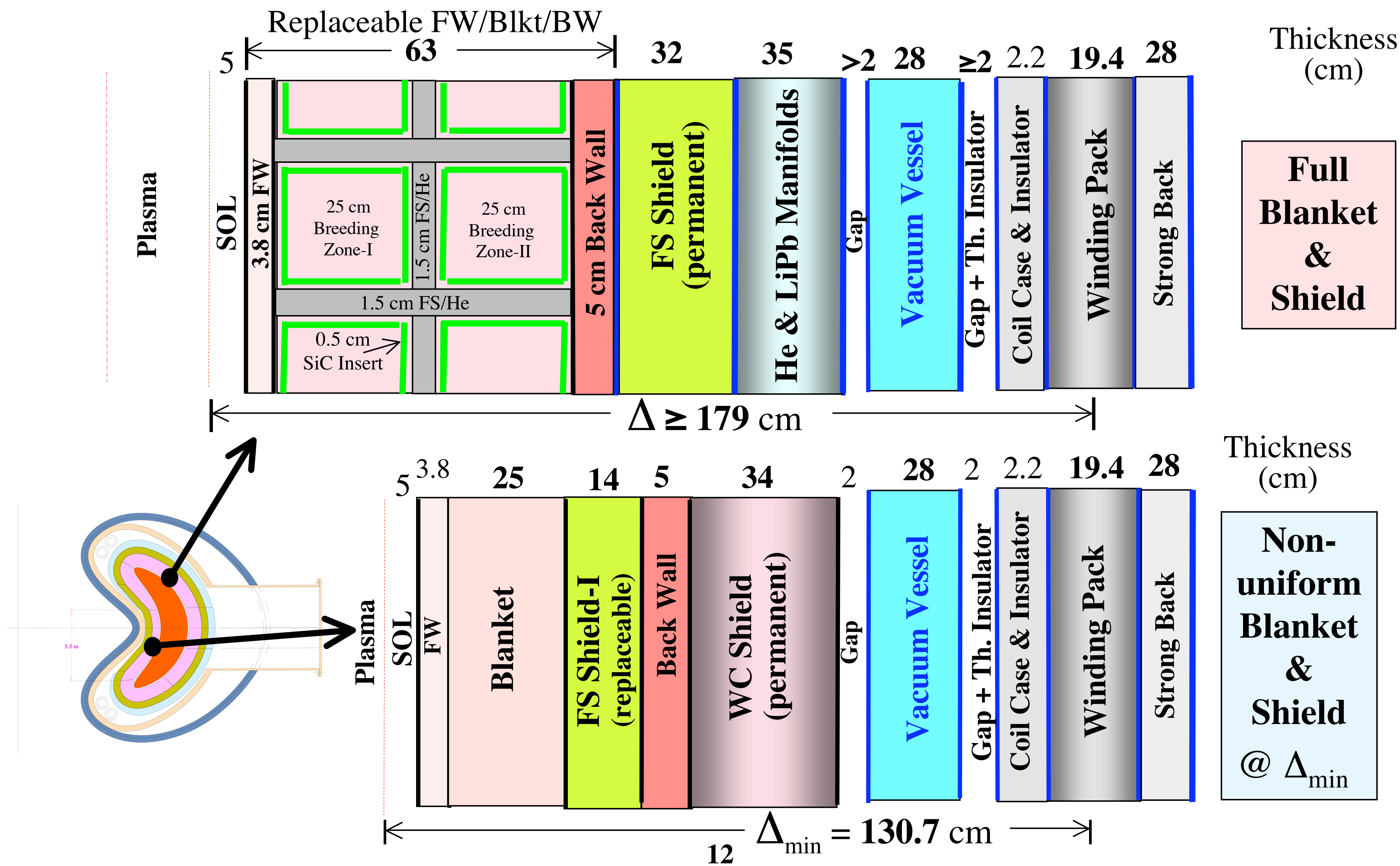


ARIES-CS Requirements Guide
In-vessel Component Design

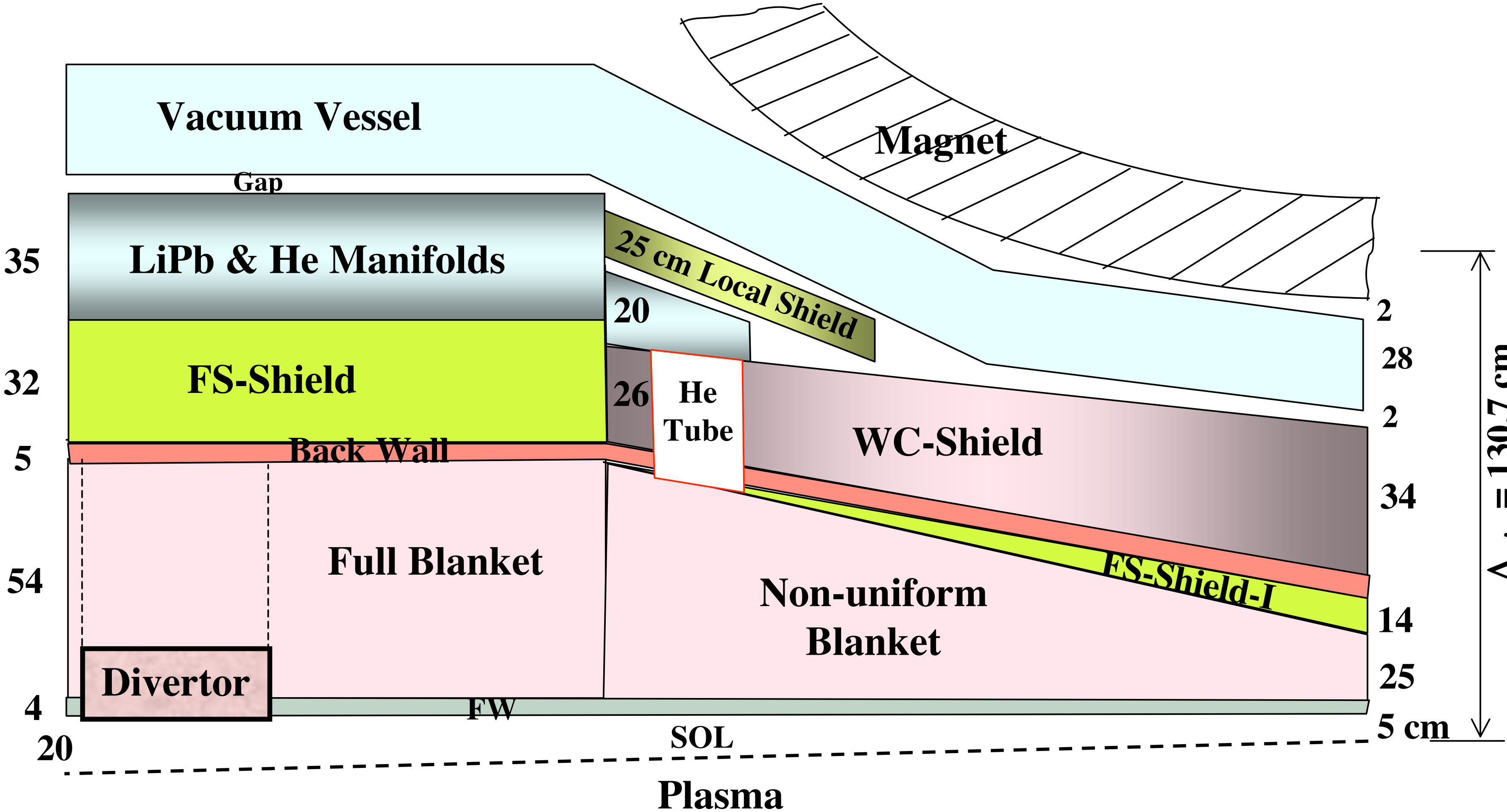
Calculated Overall TBR	1.1	
Net TBR (for T self-sufficiency)	~1.01	
Damage to Structure	200	dpa - advanced FS
(for structural integrity)	3%	Burnup – SiC/SiC
Helium Production @ Manifolds and VV (for reweldability of FS)	1	He appm
S/C Magnet (@ 4 K):		
Peak Fast n **fluence** to Nb_3Sn ($E_n > 0.1$ MeV)	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

Well-Optimized Blanket & Shield Protect Vital Components

(5.3 MW/m^2 Peak Γ)



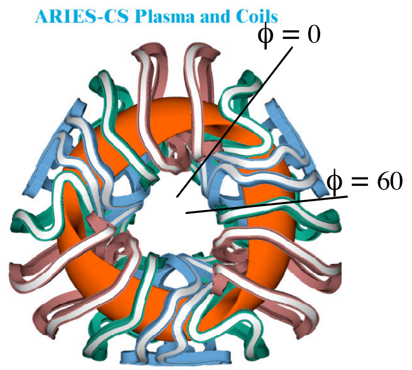
High Performance Components at Δ_{min} Help Achieve Compactness, Minimize Major Radius, and Enhance Economics

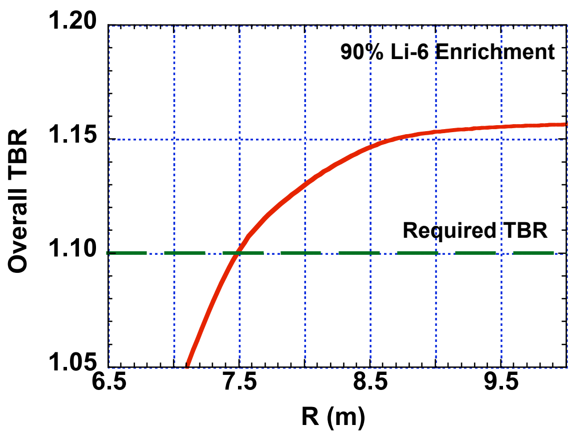


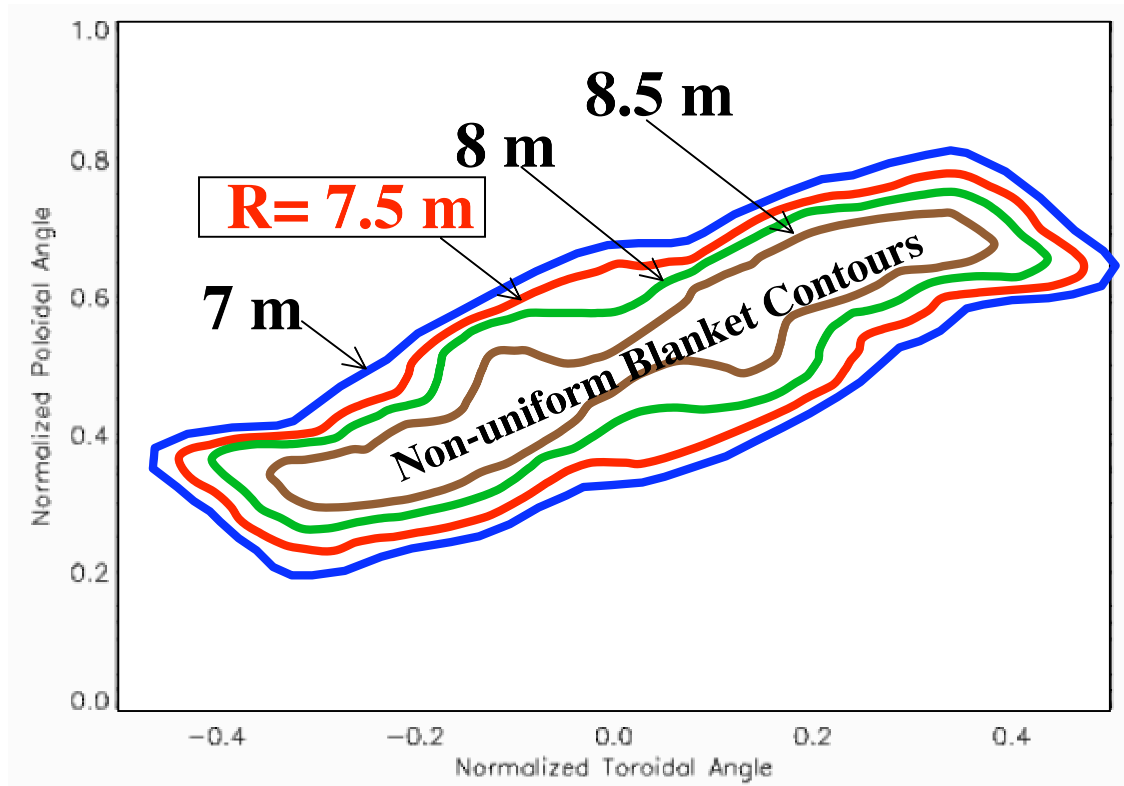
Full Blanket/Shield **and** Divertor (61%+15%= 76% of FW area)

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

Tritium Breeding Requirement Determined Minimum Major Radius





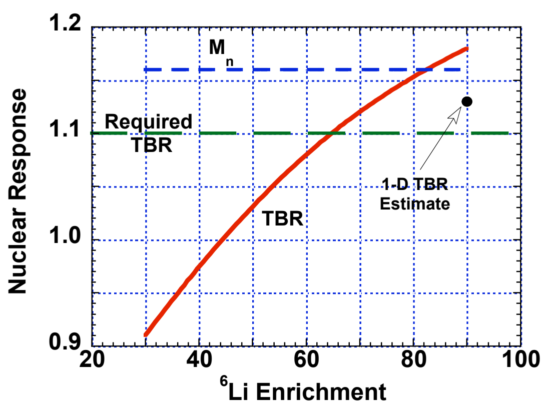


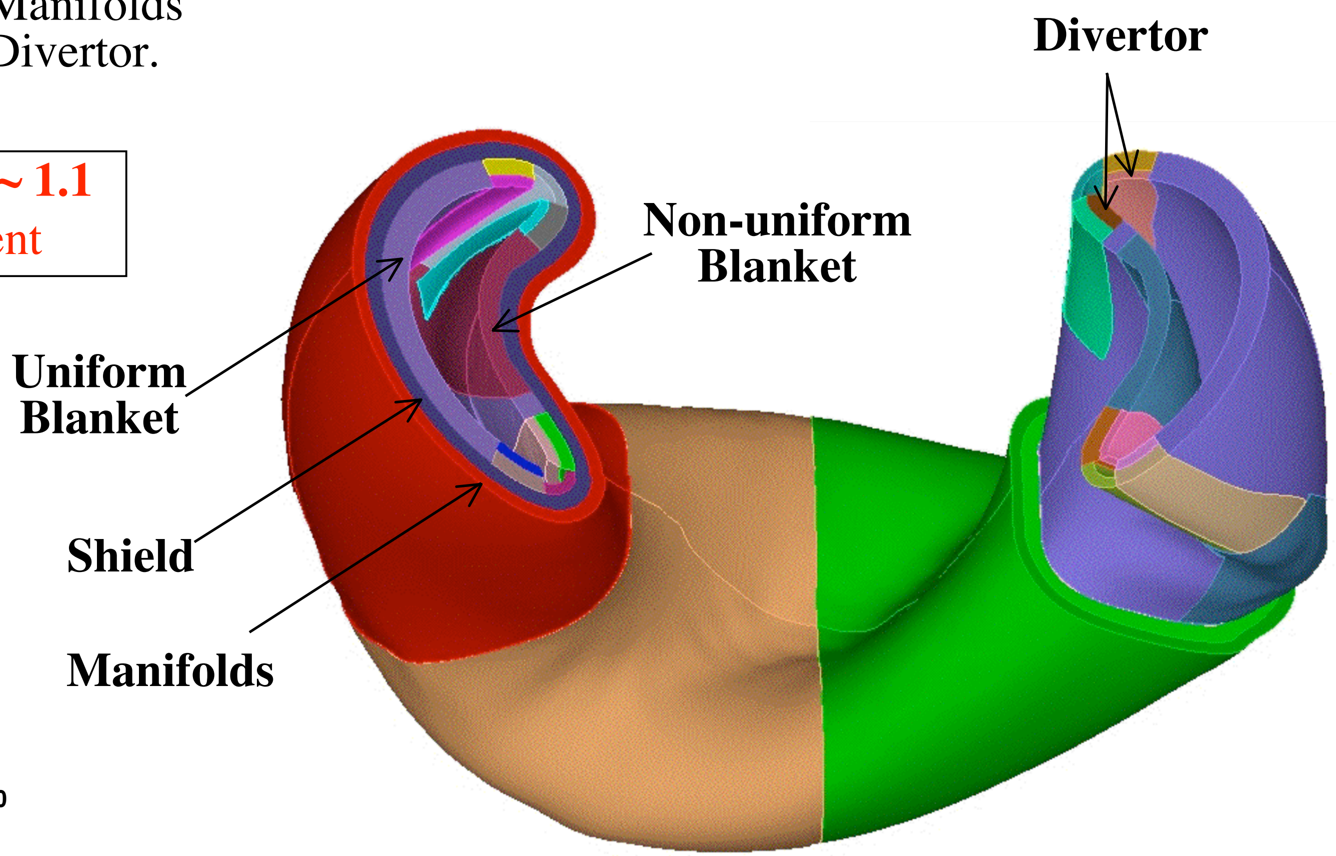
- Large machines breed more T as non-uniform blanket coverage decreases with R.
- Designs with R < 7.5 m will not provide T self-sufficiency.

R=7.75 m Reference Design Provides Tritium Self-Sufficiency

3-D model includes essential components for TBR:
- Non-uniform and full blanket/shield
- Homogenized: FW/Blanket/BW
  Shield
  Manifolds
  Divertor.

Calculated Overall **TBR ~ 1.1**
with 70% Li enrichment

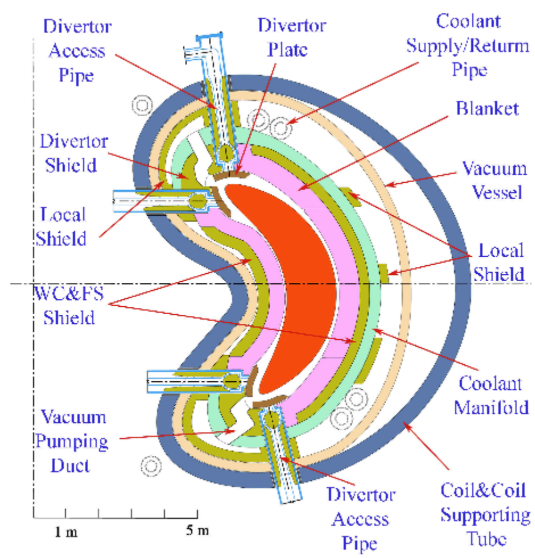


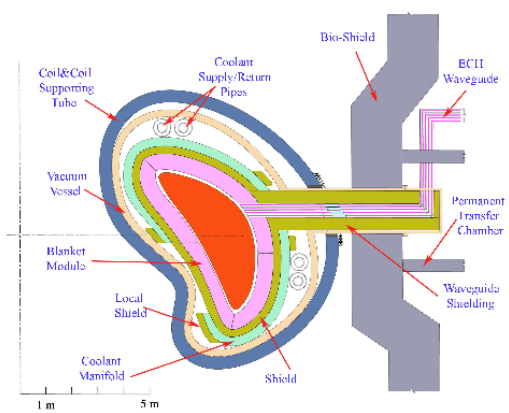


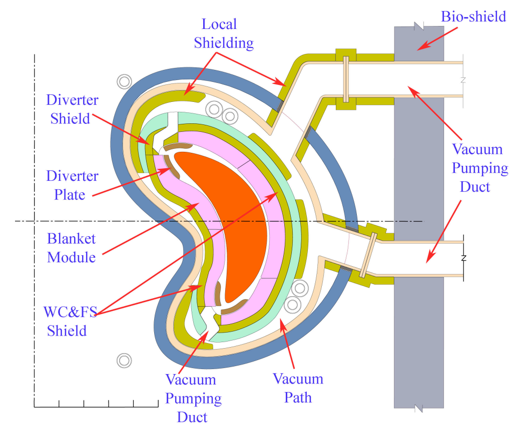
Neutron Streaming Through Penetrations Compromises Shielding Performance

- **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.





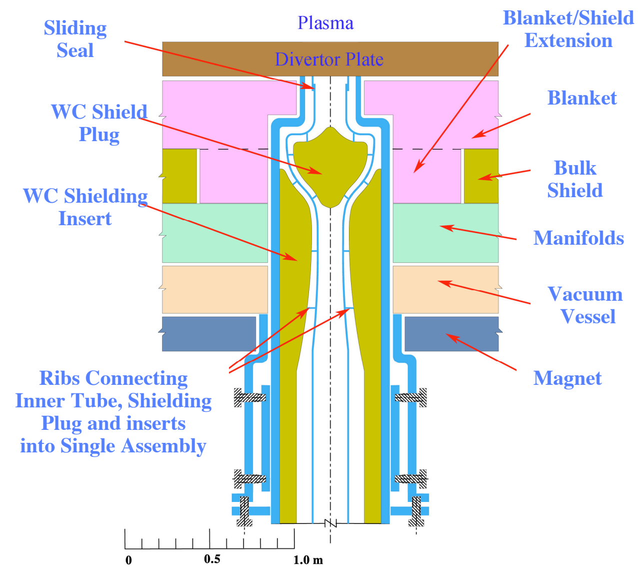


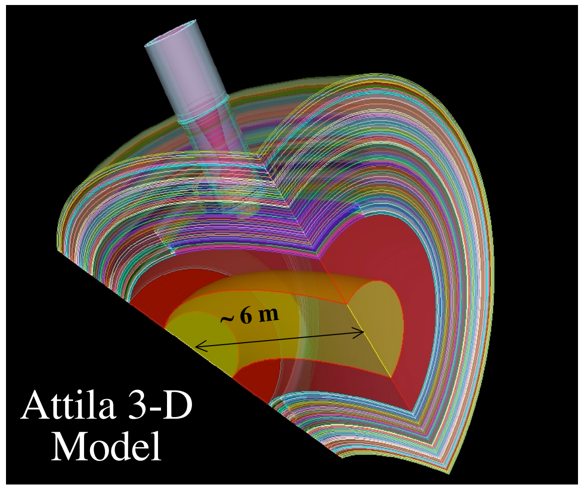
3-D Assessment of Streaming Through Divertor He-Access Pipe

- 3-D analysis indicated neutron attenuation through the WC shielding plug and inserts is not sufficient to eliminate streaming problems entirely. Potential solutions include:
  - Avoid rewelding manifolds and VV near pipe
  - Coil should be placed at least 40 cm from pipe
  - Surround pipe end with shield to protect externals.

- Future studies should develop more effective scheme to attenuate streaming neutrons and reduce flux outside pipes.

- Simple pipe with smaller ID than 60 cm and several right-angle bends represents better approach, eliminating massive WC shielding plug and inserts (170 tons for 24 pipes of ARIES-CS).





Key Nuclear Parameters

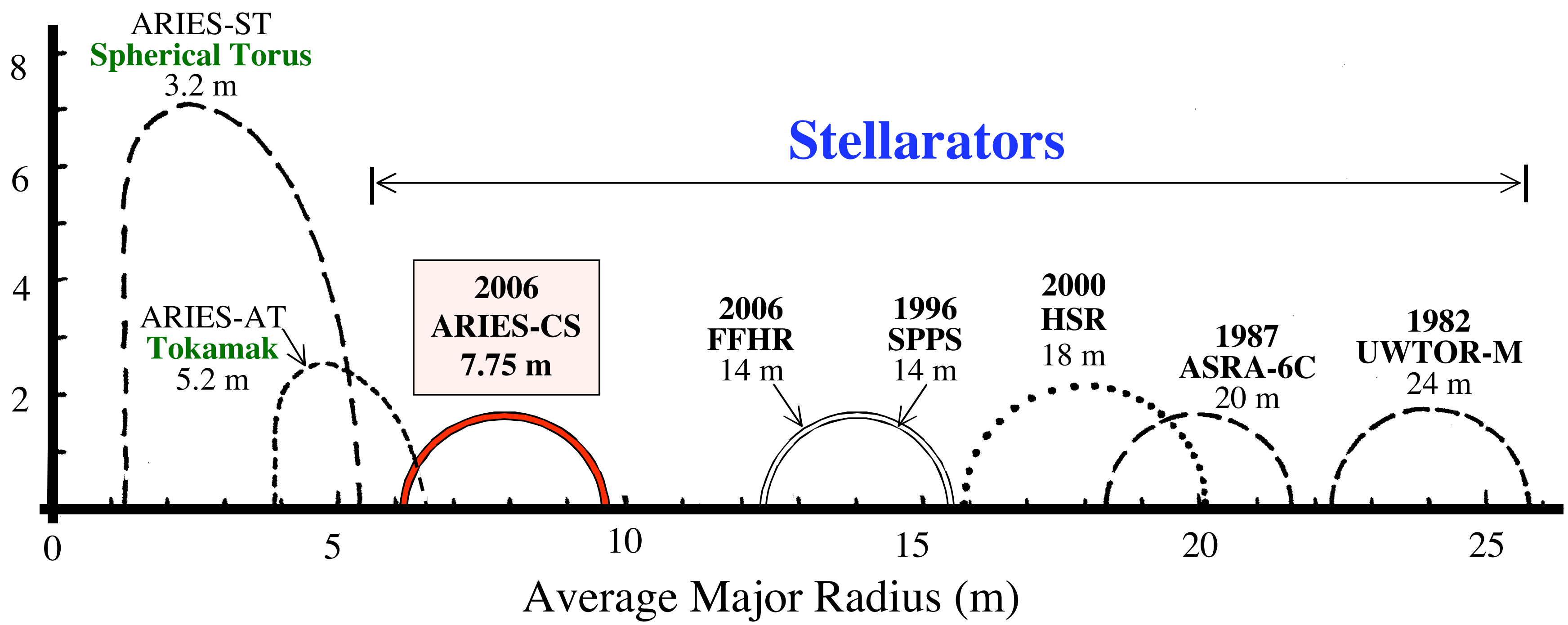
Peak NWL	**5.3 MW/m^2**
Average NWL	**2.6 MW/m^2**
Peak to Average NWL	**2**
Calculated Overall TBR	**1.1** with 70% Li enrichment
Net TBR	**~1.01**
FW/blanket Lifetime	**3 FPY**
Shield/manifold/VV/magnet Lifetime	**40 FPY**
Overall Energy Multiplication	**1.16**
Δ_{min}	**1.3 m**
Δ_{max}	**1.8 m**

Comparison Between Reference and Backup Systems

	LiPb/He/FS	LiPb/SiC
Calculated Overall **TBR**	1.1	1.1
FW/blanket **lifetime**	3 FPY	3.4 FPY
Overall **energy multiplication**	1.16	1.1
η_{th}	42%	56%
Structure **unit cost***	103 $/kg	510 $/kg
Blanket/divertor/shield/manifolds **cost***	$288M	$282M
Cost* of **heat transfer/transport system**	$475M	$175M
Pumping power	183 MW_e	---
LSA factor	2	1
Cost of Electricity*:		
Reference design (R=7.75 m)	**78** mills/kWh	**60** mills/kWh
Full blanket/shield everywhere (R=10.1 m)	**87** mills/kWh	

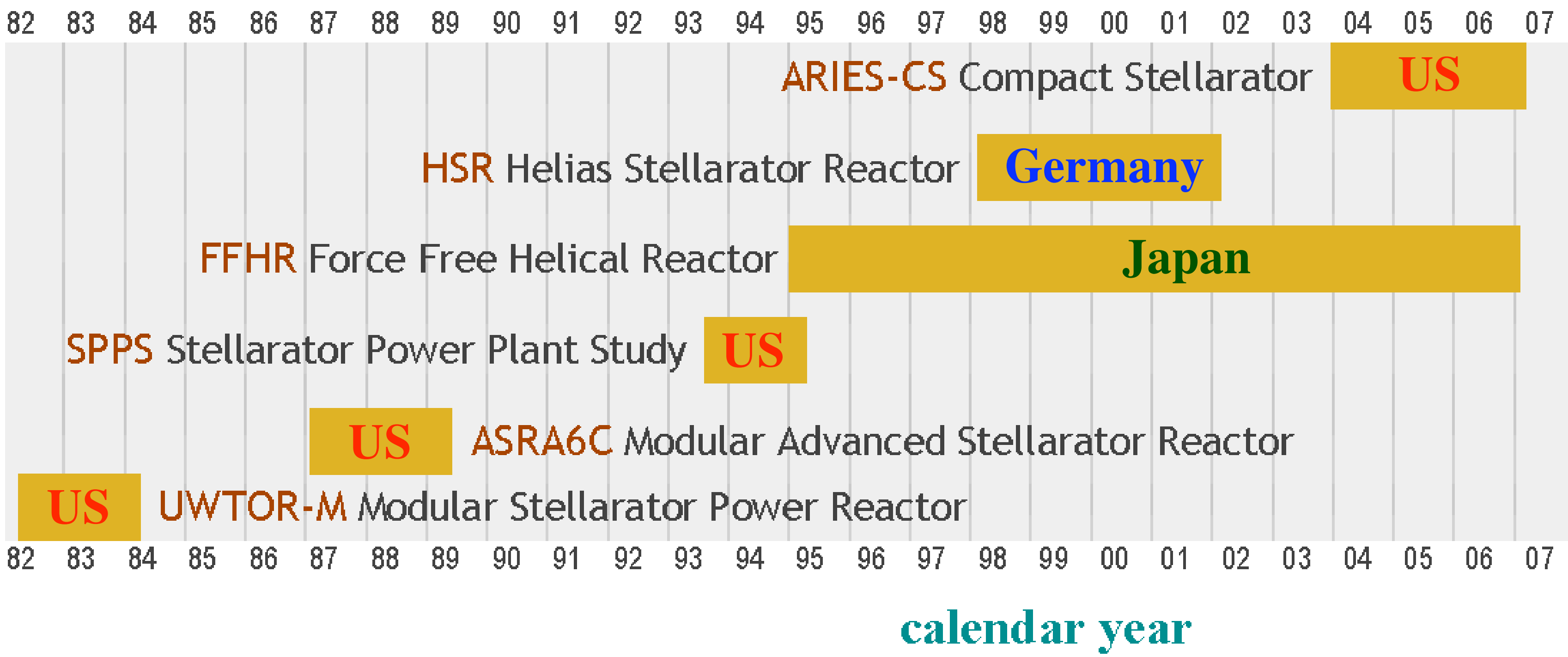
* in 2004 $.

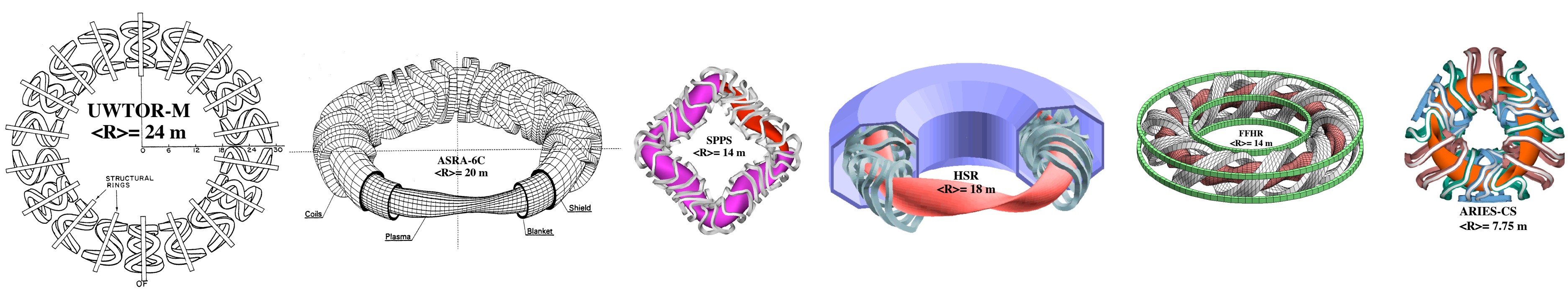
Well Optimized Radial Build along with Advanced Physics and Technologies Helped Reduce ARIES-CS Dimensions



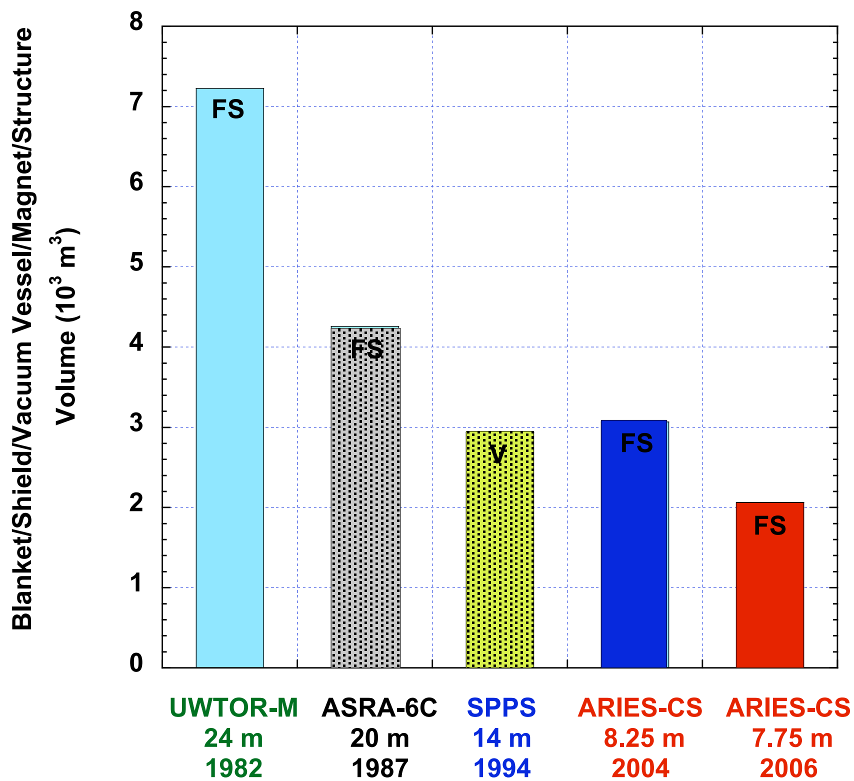
ARIES-CS major radius approaches that of advanced tokamaks

Six Stellarator Power Plants Developed Worldwide Over Past 25 y





ARIES Project Committed to Radwaste Minimization



Stellarator waste volume dropped by 3-fold over 25 y study period

* Actual volumes (not compacted, no replacements).

Highlights of ARIES-CS Safety and Environmental Features

Environmental impact:

– **Low activation materials** with strict impurity control
  ⇒ minimal long-term environmental impact.

– **No high-level waste**.

– **Minimal radioactive releases**# during normal and abnormal operations.

No energy and pressurization threats to confinement barriers (VV and cryostat):

– Decay heat problem solved by design
– Chemical reaction avoided
– No combustible gas generated
– Chemical energy controlled by design
– Overpressure protection system
– Rapid, benign plasma shutdown.

Occupational and public safety:

– **No evacuation plan** following abnormal events (early dose at site boundary < 1 rem*) to avoid disturbing public daily life.

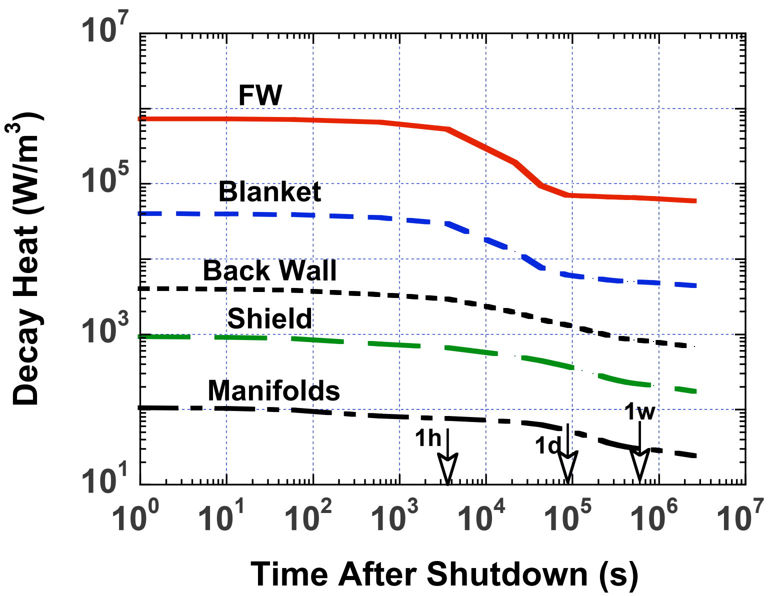
– **Low dose** to workers and personnel during operation and maintenance activity (< 2.5 mrem/h*).

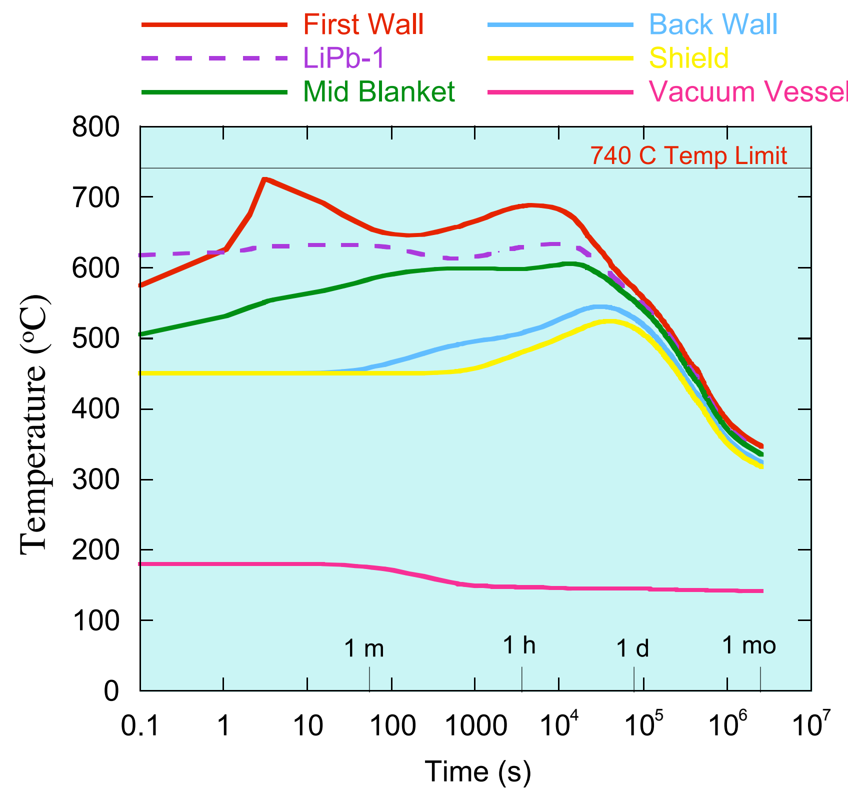
– **Public safety** during normal operation (bio-dose << 2.5 mrem/h*) and following credible accidents:
  - External events (seismic, hurricanes, tornadoes, etc.).
  - LOCA, LOFA, LOVA, and by-pass events.

Such as T, volatile activated structure, corrosion products, and erosion dust. Or, from liquid and gas leaks.

* 1 rem (= 10 m Sv) accident dose stated in Fusion Safety Standards, DOE report, DOE-STD-6002-96 (1996).

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 FW temperature remains below 740ºC – reusability limit for ferritic steel.

Radwaste Management Approach

- **Three options examined**:
  - **Disposal** in repositories: LLW (WDR < 1)
  - **Recycling** – reuse within nuclear facilities (dose < 10,000 Sv/h)
  - **Clearance** – release slightly-radioactive materials to commercial market if CI < 1.

- Lack of geological repositories and tighter environmental controls will force fusion designers to promote recycling and clearance, avoiding disposal*

  ⇒ **minimize radwaste burden for future generations**.

- There's **growing international effort** in support of this new trend.

* L. El-Guebaly, "Recent Trend in Managing Fusion Radwaste: Recycling and Clearance, Avoiding Disposal," 2008 US/J Workshop, Thursday March 6 @ 9:50 AM.

Conclusions

- Nuclear assessment received considerable attention during ARIES-CS design process.
- First time ever complex stellarator geometry modeled for nuclear assessment using UW newly developed CAD/MCNPX coupling approach.
- Radial build satisfies design requirements in terms of breeding sufficient tritium and shielding vital components.
- Novel shielding approach developed for ARIES-CS helped reduce radial standoff by 40%, major radius by 30%, and overall cost by 10%.
- ARIES-CS demonstrates adequate performance in several safety and environmental areas.
- Successful integration of well-optimized radial build into final design, along with carefully selected engineering parameters and overarching safety and environmental constraints, delivered attractive and <u>truly compact stellarator power plant.</u>

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, 432-439 (2005).

- L. El-Guebaly, P. Wilson, D. Henderson, M. Sawan, G. Sviatoslavsky, T. Tautges, R. Slaybaugh, B. Kiedrowski, A. Ibrahim, and The ARIES Team, "Nuclear Challenges and Progress in Designing Stellarator Power Plants," presented at 13th International Conference on Emerging Nuclear Energy Systems, ICENES-2007, Istanbul, Turkey. To be published in Energy Conversion & Management Journal.

- C. Martin and L. El-Guebaly, "ARIES-CS Loss of Coolant and Loss of Flow Accident Analyses," Fusion Science and Technology, **52**, No. 3, 985-989 (2007).

- L. El-Guebaly, P. Wilson, D. Henderson, M. Sawan, G. Sviatoslavsky, T. Tautges, R. Slaybaugh, B. Kiedrowski, A. Ibrahim, C. Martin, and the ARIES-CS team, "Overview of ARIES-CS In-vessel Components: Integration of Nuclear, Economics, and Safety Constraints in Compact Stellarator," Proceedings of 2nd IAEA TM on First Generation of Fusion Power Plants: Design & Technology, June 20 - 22, 2007, Vienna, Austria. Proceedings to be published by IAEA on CD.

- A. Ibrahim, D.L. Henderson, L.A. El-Guebaly, P.P.H. Wilson, and M.E. Sawan, "Assessment of Radiation Streaming Through ARIES-CS He-Access Pipes using Two- and Three-Dimensional Analyses," University of Wisconsin Fusion Technology Institute Report, UWFDM-1331 (Dec. 2007). Available at: http://fti.neep.wisc.edu/pdf/fdm1331.pdf.

- L. El-Guebaly, P. Wilson, D. Henderson et al. "Designing ARIES-CS Compact Radial Build and Nuclear System: Neutronics, Shielding, and Activation," to be published in Fusion Science and Technology.