# Nuclear Challenges and Progress in Designing Stellarator Power Plants

L. El-Guebaly,

P. Wilson, D. Henderson, M. Sawan, G. Sviatoslavsky,
T. Tautges, R. Slaybaugh, B. Kiedrowski, A. Ibrahim,
and the ARIES Team

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

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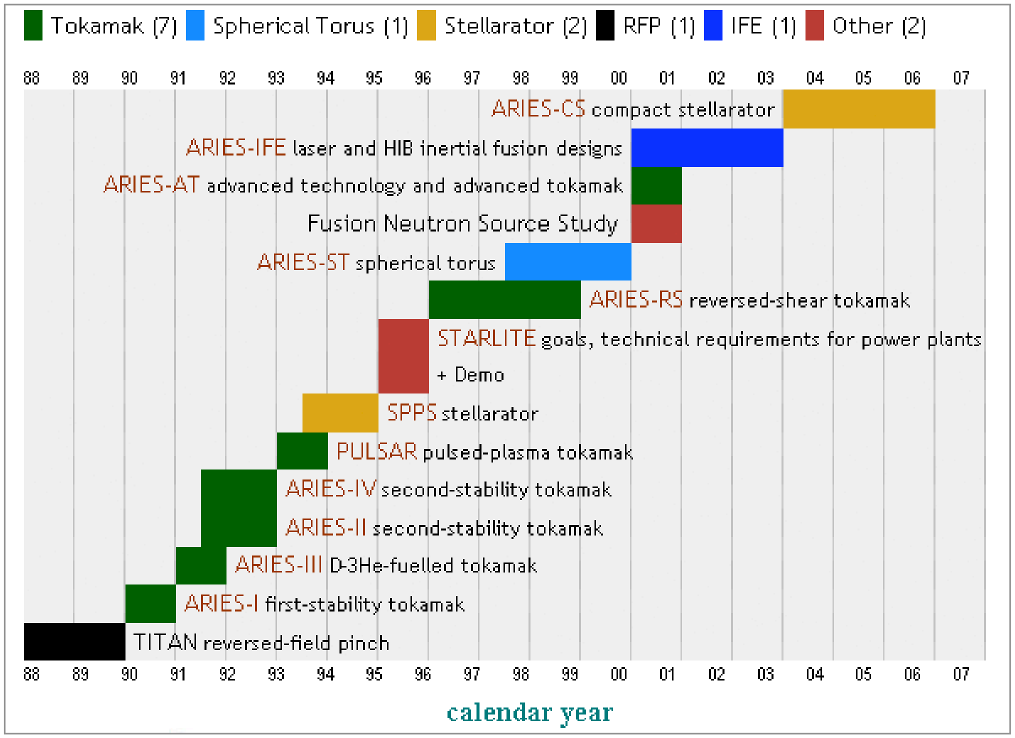
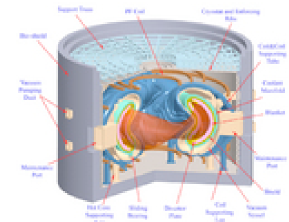
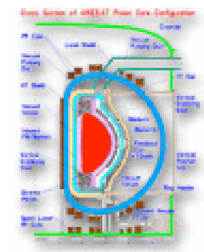
# Multi-Institution ARIES Project





ARIES-CS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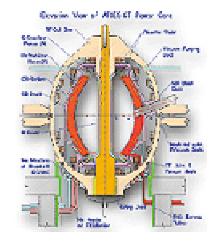
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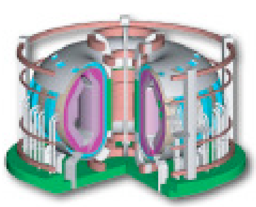
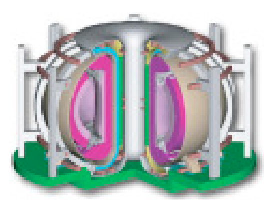

ARIES-I


ARIES-III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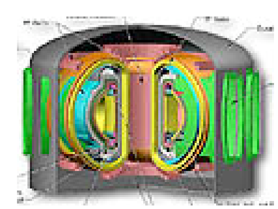
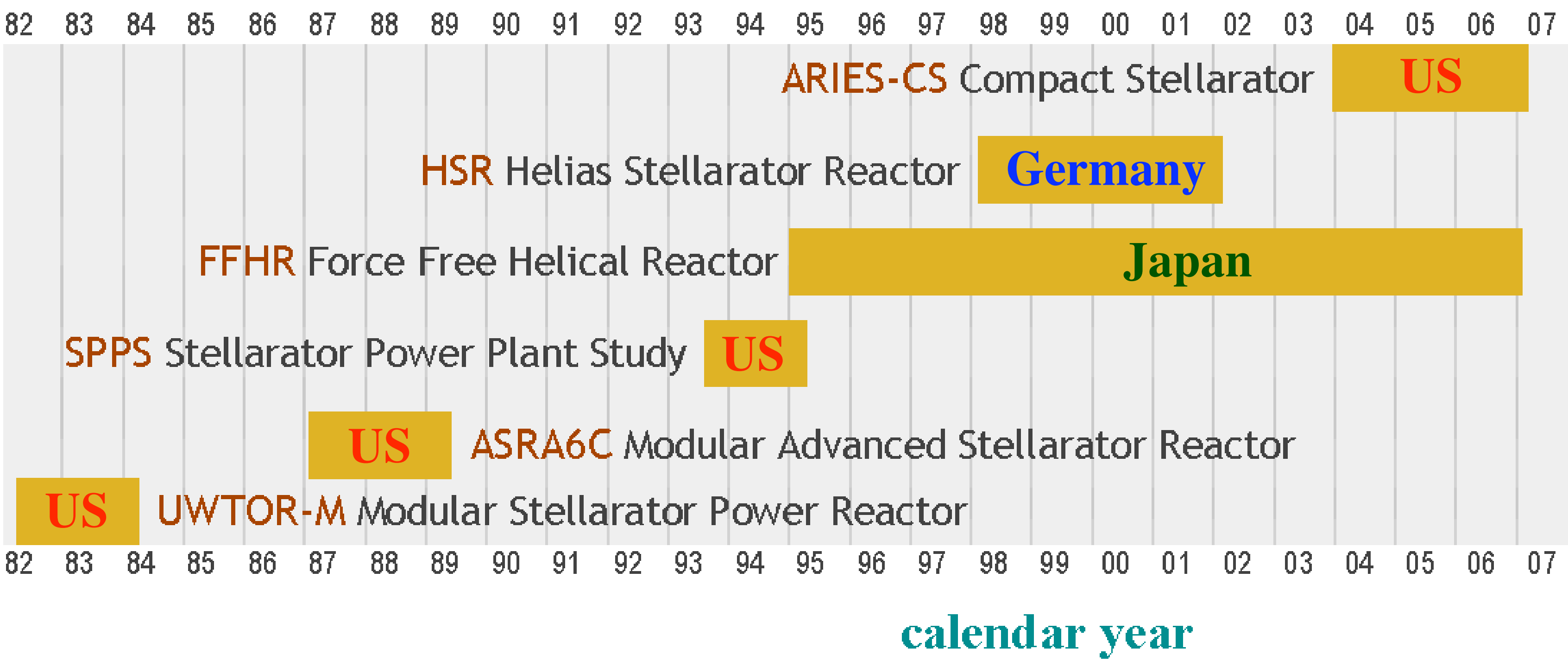
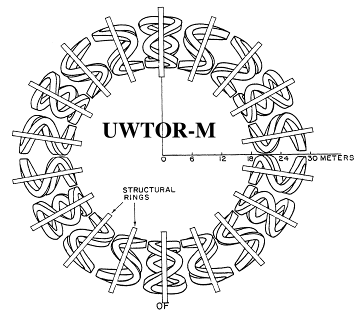
SPPS

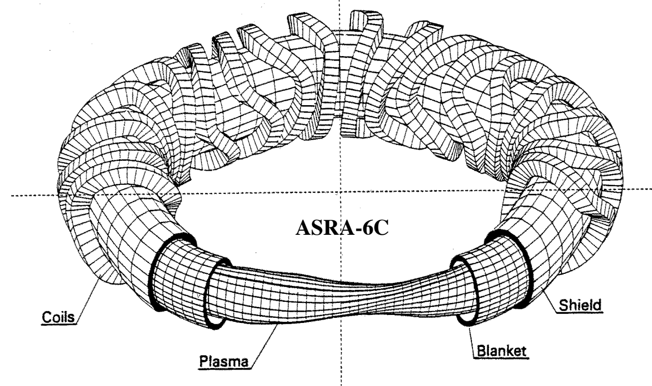

ARIES-RS

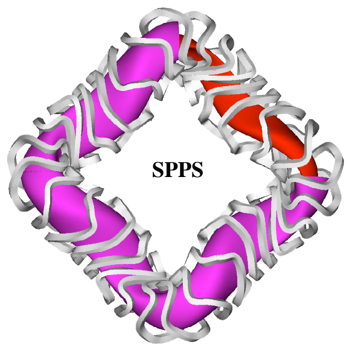
# Six Stellarator Power Plants Developed Worldwide Over Past 25 y

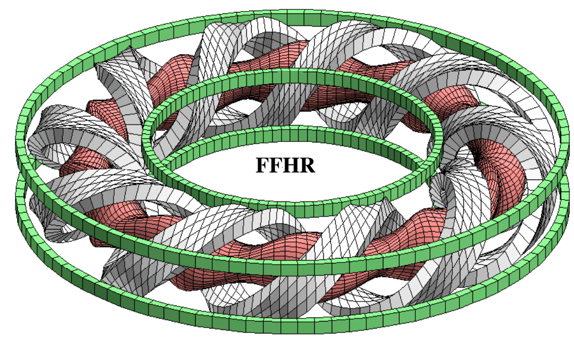


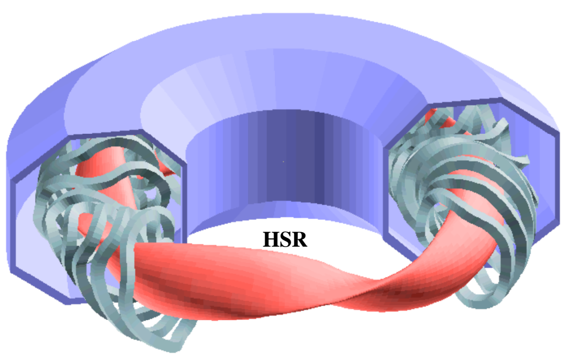
# Six Stellarator Power Plants Developed Worldwide Over Past 25 y (Cont.)

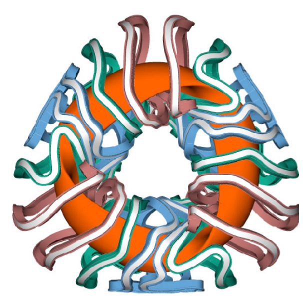




ARIES-CS

# 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.

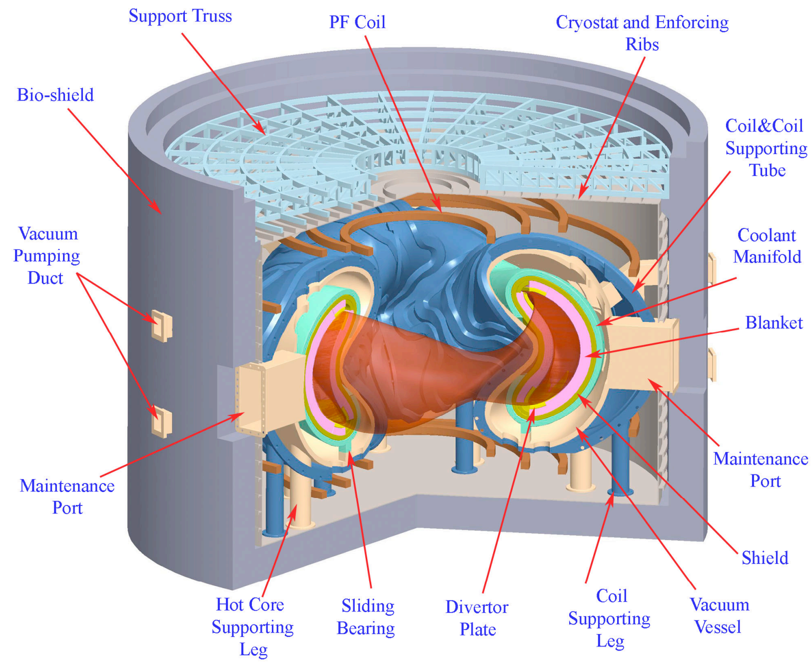
**Challenges**:

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

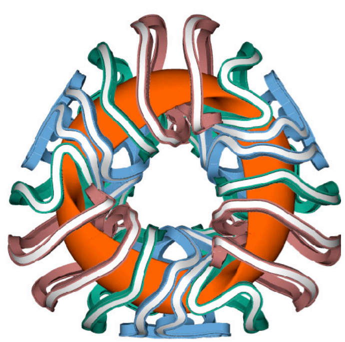
# ARIES Compact Stellarator

**Study aimed at reducing stellarators' size** by:

- Developing compact configuration with advanced physics & technology
- **Optimizing minimum plasma-coil distance ($\Delta_{min}$) through rigorous nuclear assessment.**



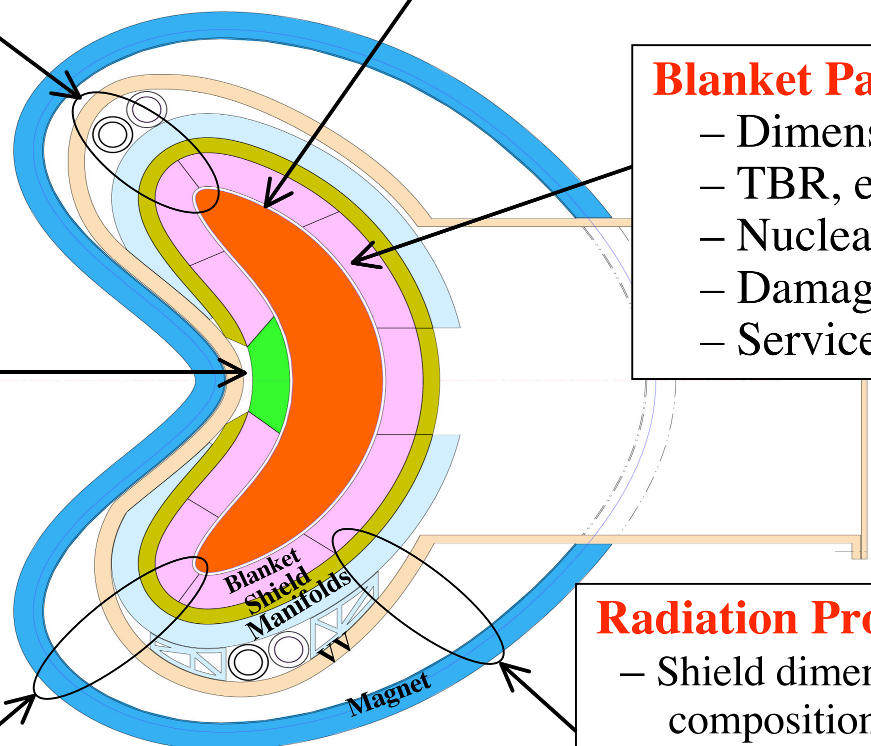

| 3 Field Periods Configuration | |
|---|---|
| Average Major Radius | 7.75 m |
| Average Minor Radius | 1.7 m |
| Aspect Ratio | 4.5 |
| Fusion Power | 2400 MW |
| Average NWL | 2.6 $MW/m^2$ |
| Net Electric Power | 1000 $MW_e$ |
| COE ($2004) | 78 mills/kWh |



# 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 $\Delta_{min}$**

**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

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

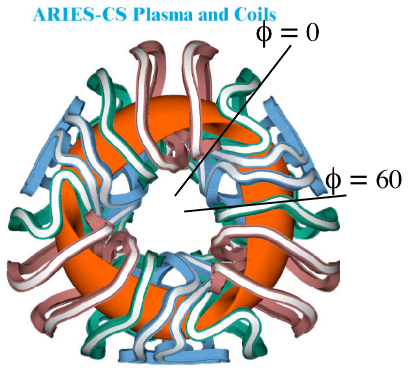
| Breeder | Multiplier | Structure | FW/Blanket Coolant | Shield Coolant | VV Coolant |
|---|---|---|---|---|---|
| **Internal VV*:** | | | | | |
| Flibe | Be | FS | Flibe | Flibe | $H_2O$ |
| **LiPb** (backup) | **–** | SiC | **LiPb** | **LiPb** | $\mathbf{H_2O}$ |
| **LiPb** (reference) | **–** | **FS**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

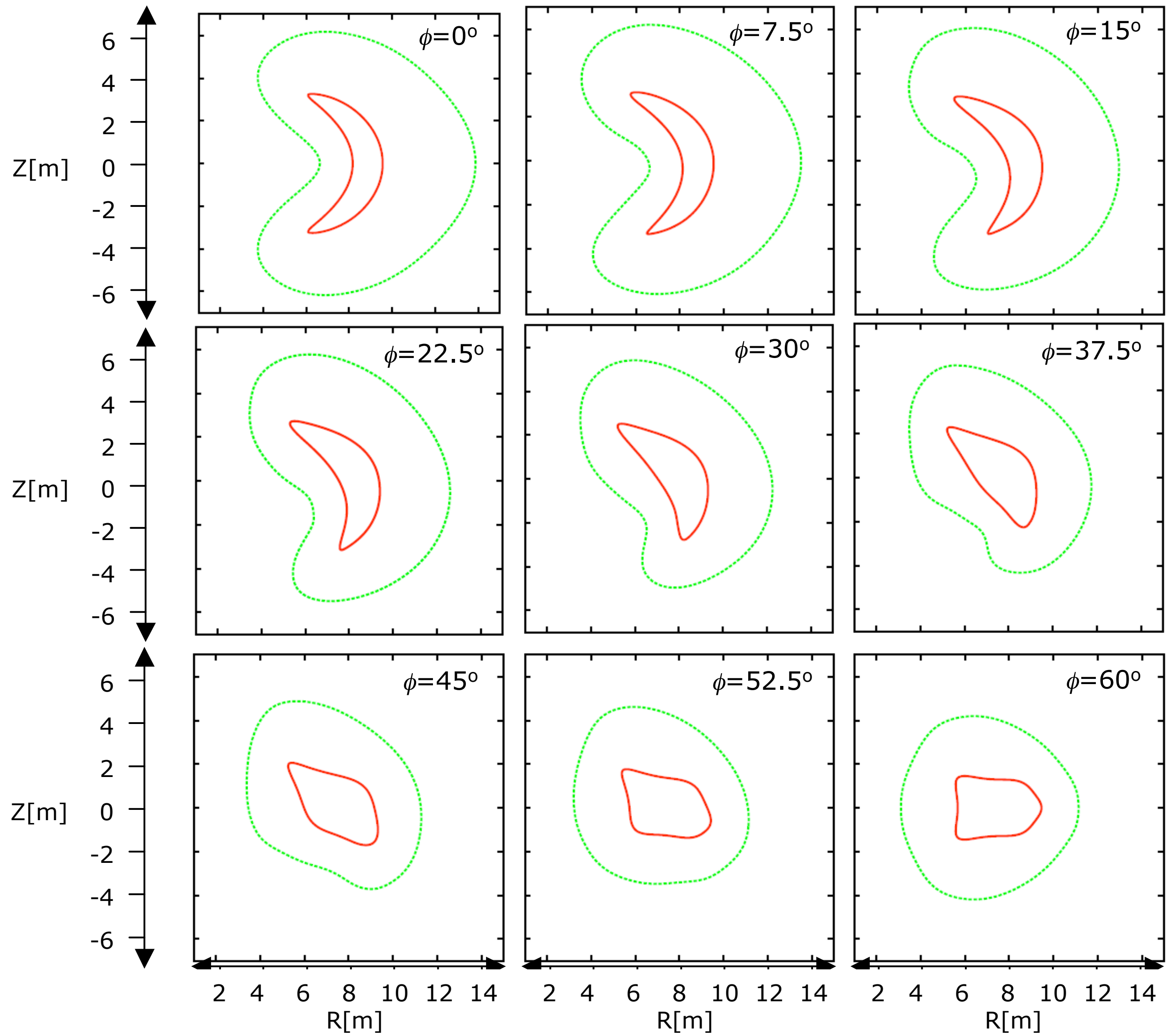
* VV inside magnets.
\# VV outside magnets.

# ARIES-CS Requirements Guide
# In-vessel Component Design

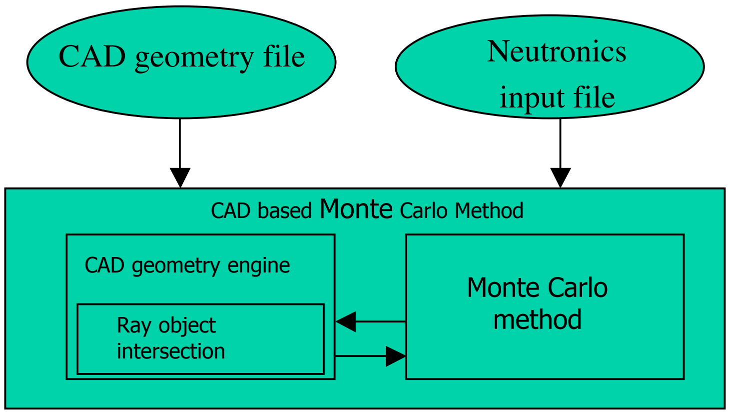
| | | |
|---|---|---|
| **Overall TBR**<br>(for T self-sufficiency) | 1.1 | |
| **Damage to Structure**<br>(for structural integrity) | 200 | dpa - advanced FS |
| **Helium Production @ Manifolds and VV**<br>(for reweldability of FS) | 1 | He appm |
| **S/C Magnet (@ 4 K):** | | |
| Peak Fast n **fluence** 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 | $6 \times 10^{-3}$ | 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

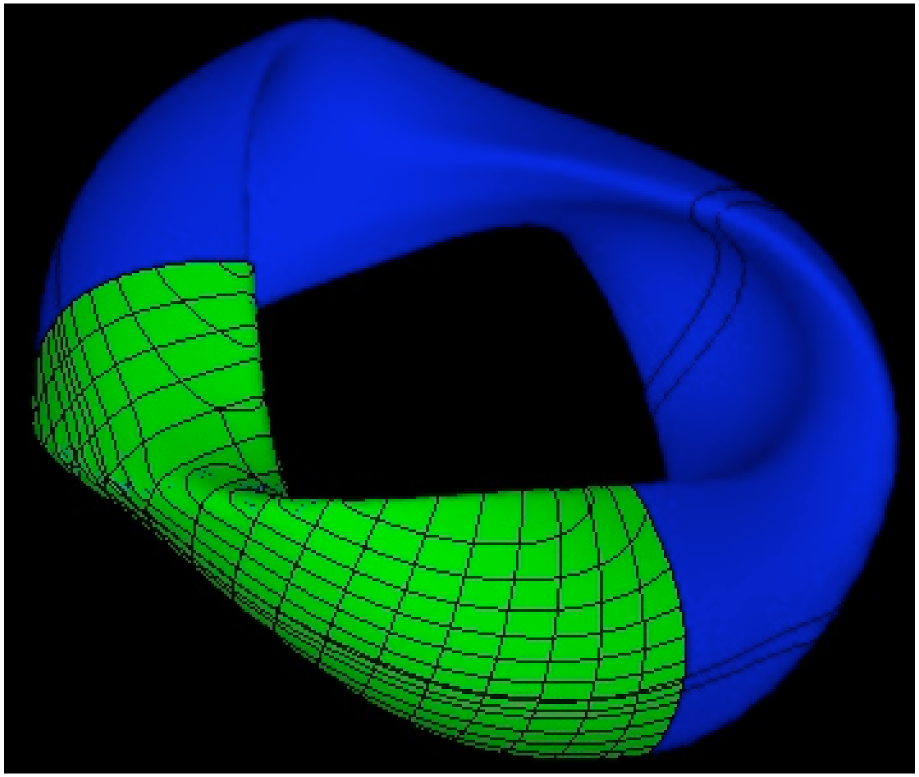


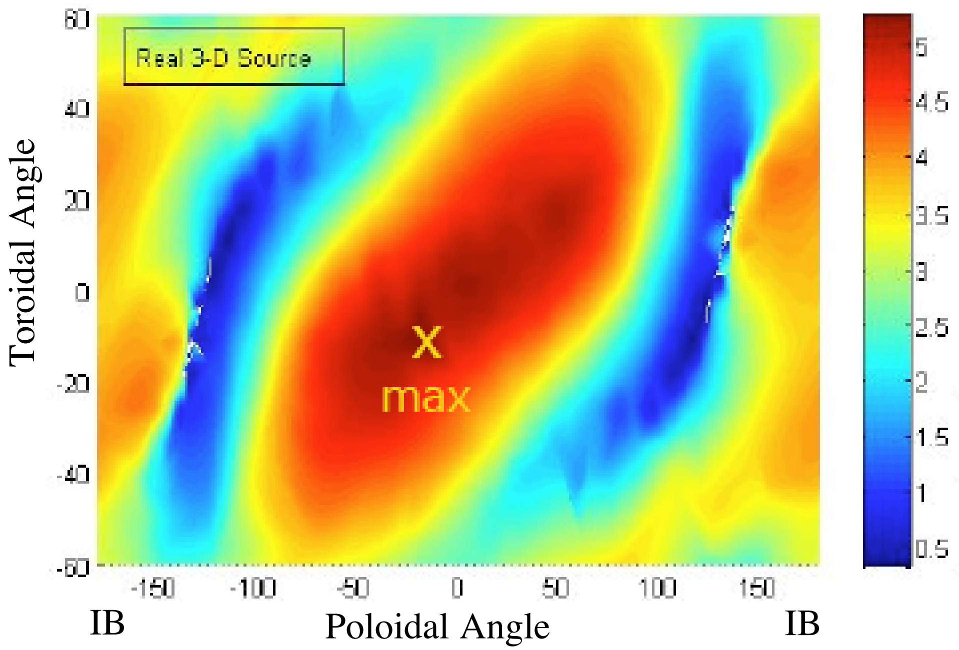
# UW Developed CAD/MCNP Coupling Approach to Model ARIES-CS for Nuclear Assessment

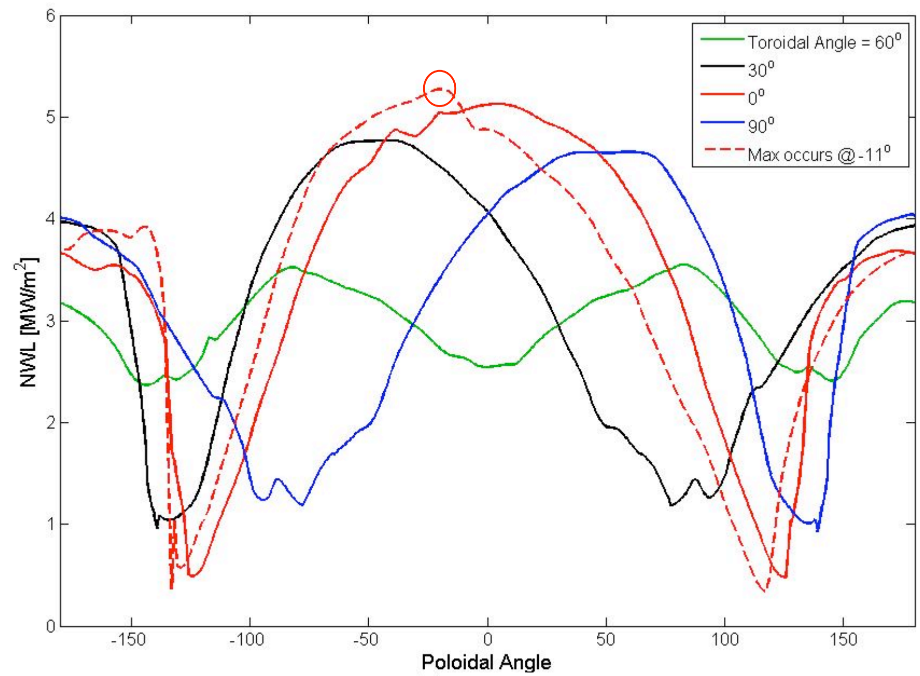



- Only viable approach for ARIES-CS 3-D neutronics modeling.
- Geometry and ray tracing in CAD; radiation transport physics in MCNPX.

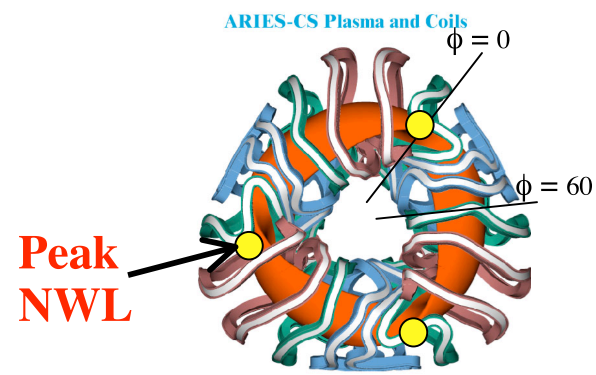


# Neutron Wall Loading Distribution



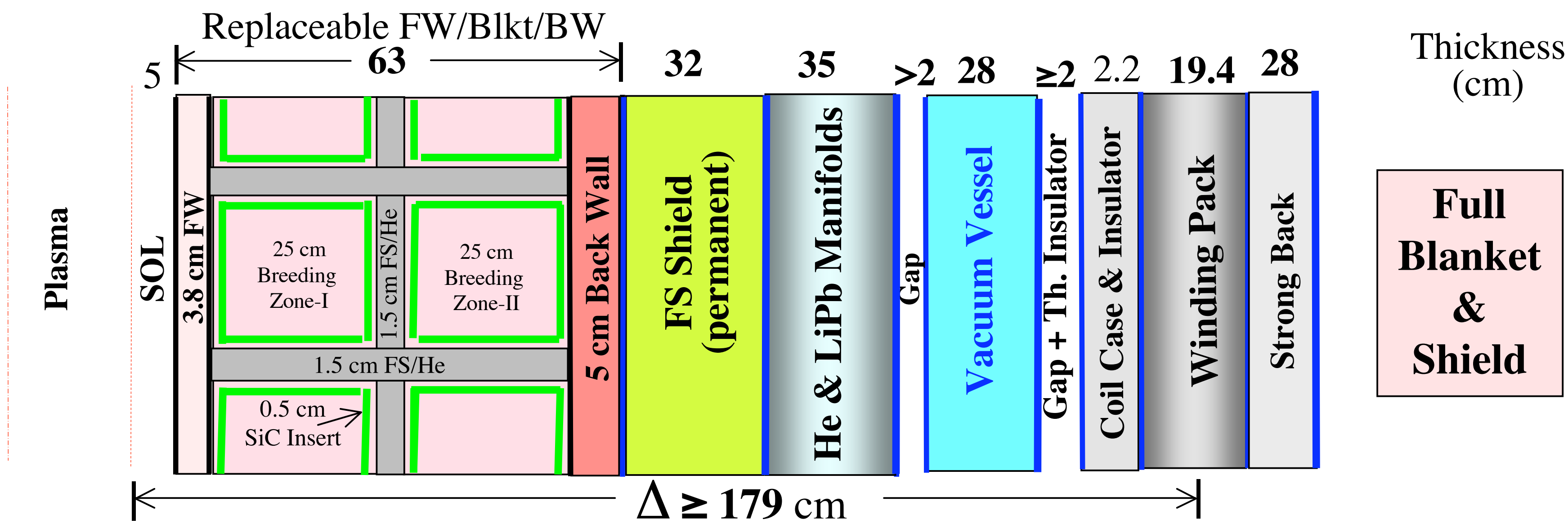



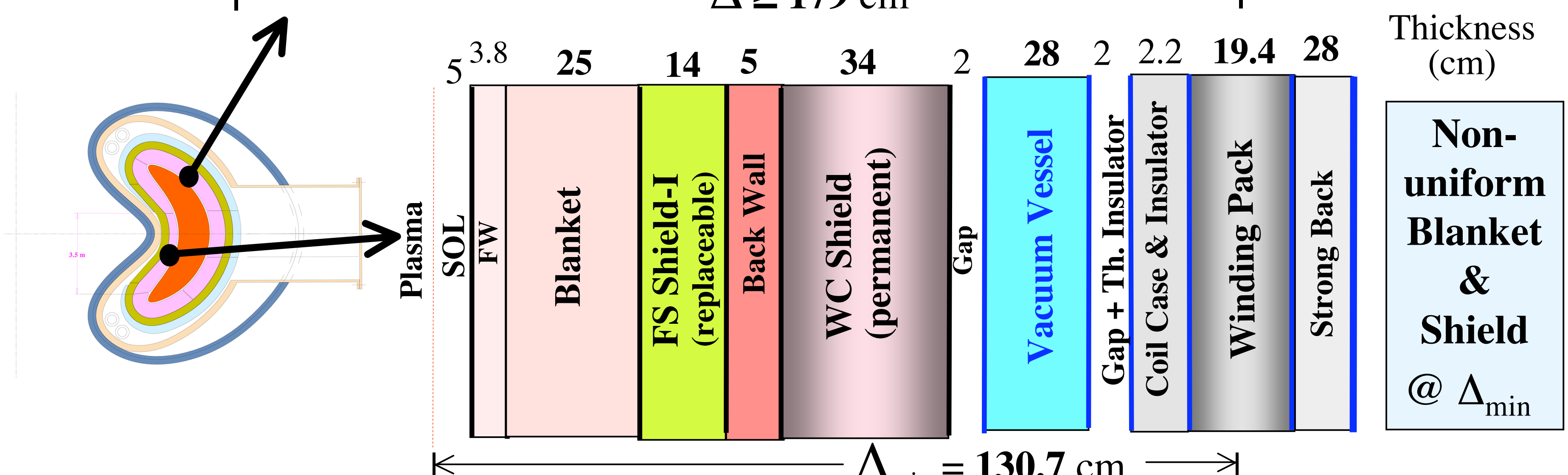

| | Peak (Min) [MW/m²] | Toroidal Angle (degrees) | Poloidal Angle (degrees) |
|---|---|---|---|
| | 5.26 (0.32) | -11 (-4) | -18 (-116) |



# Well-Optimized Blanket & Shield Protect Vital Components

(5.3 MW/m² Peak Γ)

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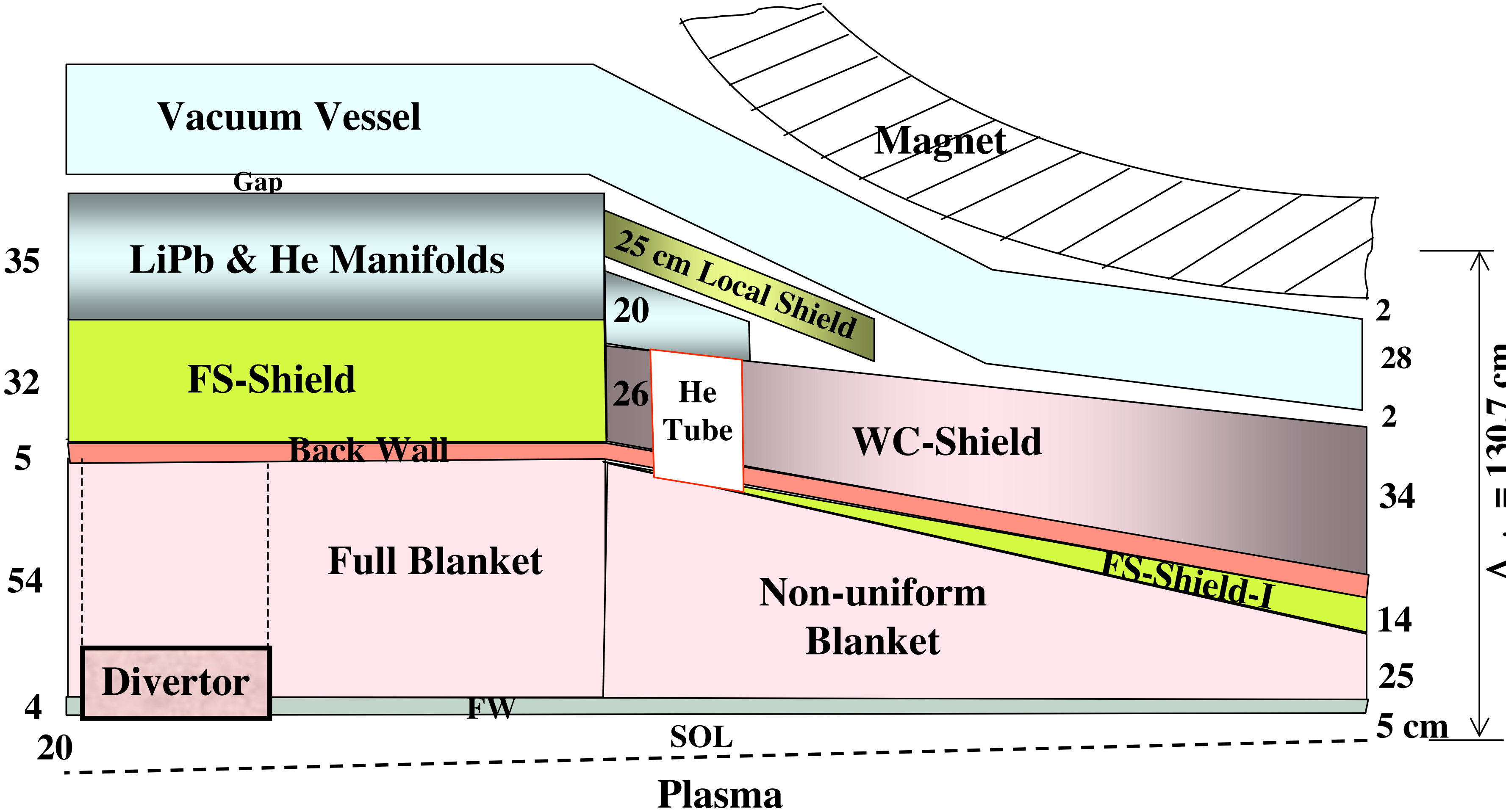
# High Performance Components at $\Delta_{min}$ Help Achieve Compactness, Minimize Major Radius, and Enhance Economics




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

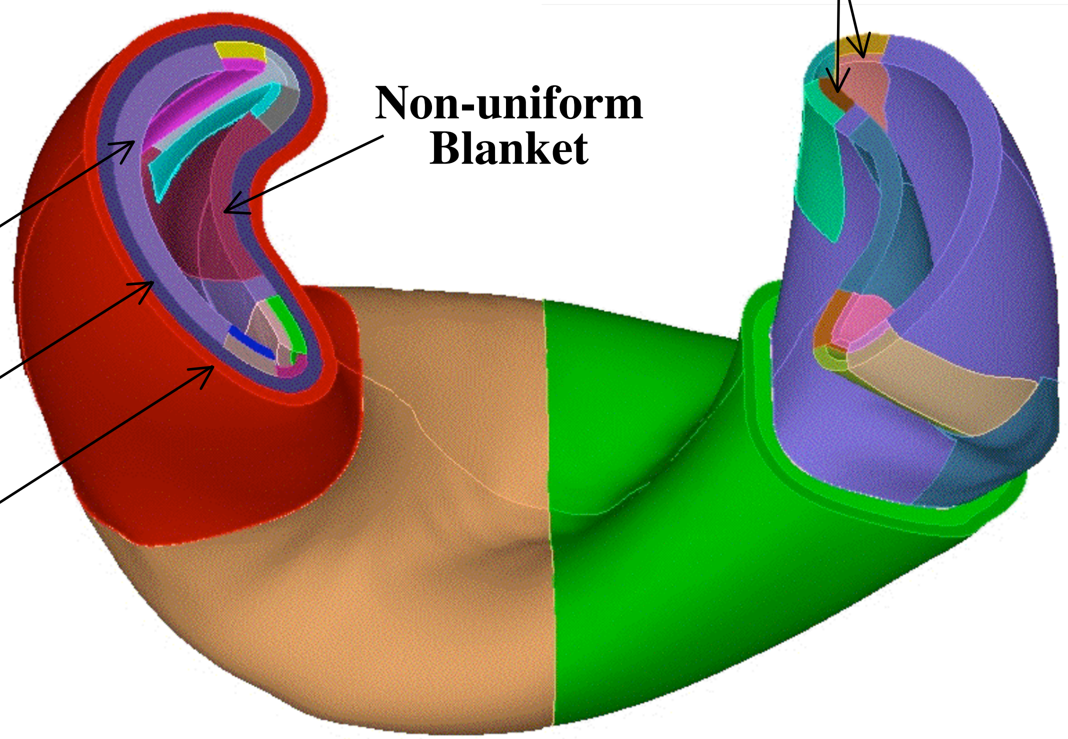
Non-uniform, Tapered Blanket/Shield (24% of FW area)

# Reference Blanket 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.

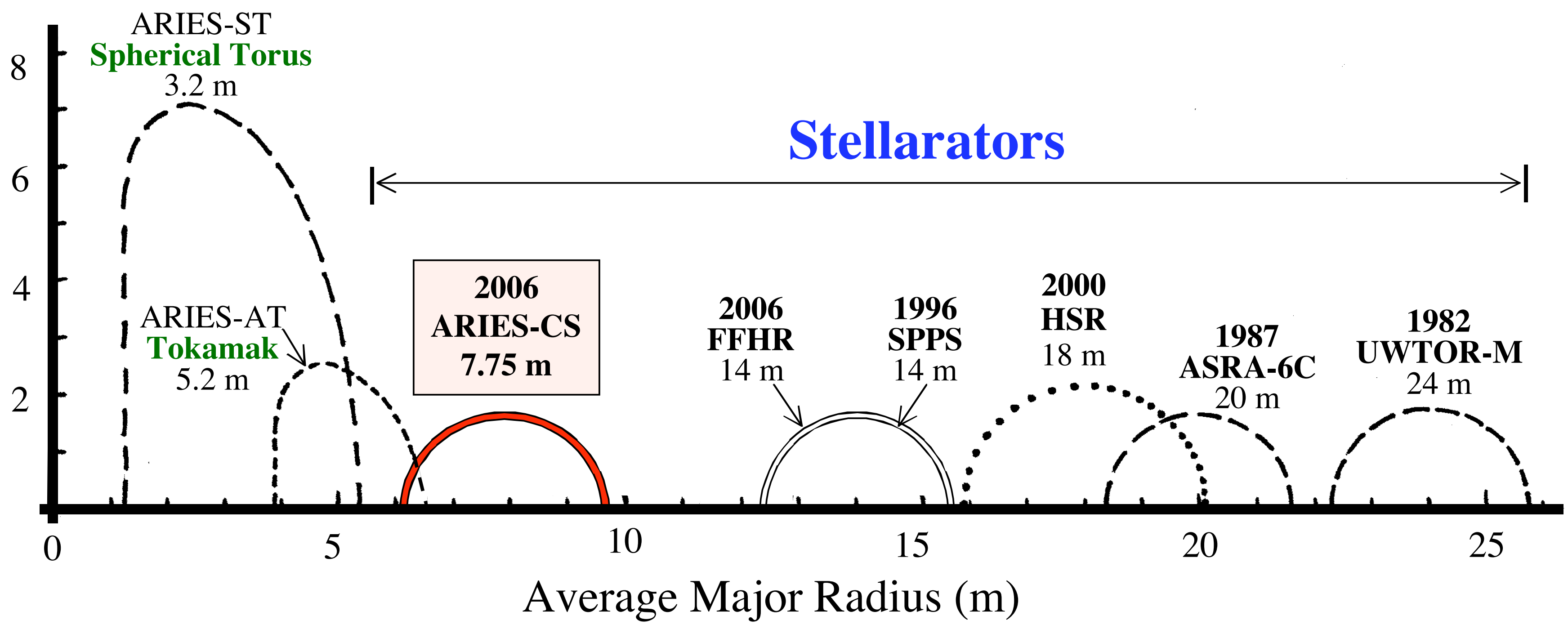
Overall **TBR = 1.1**
with 70% Li enrichment



# Key Nuclear Parameters

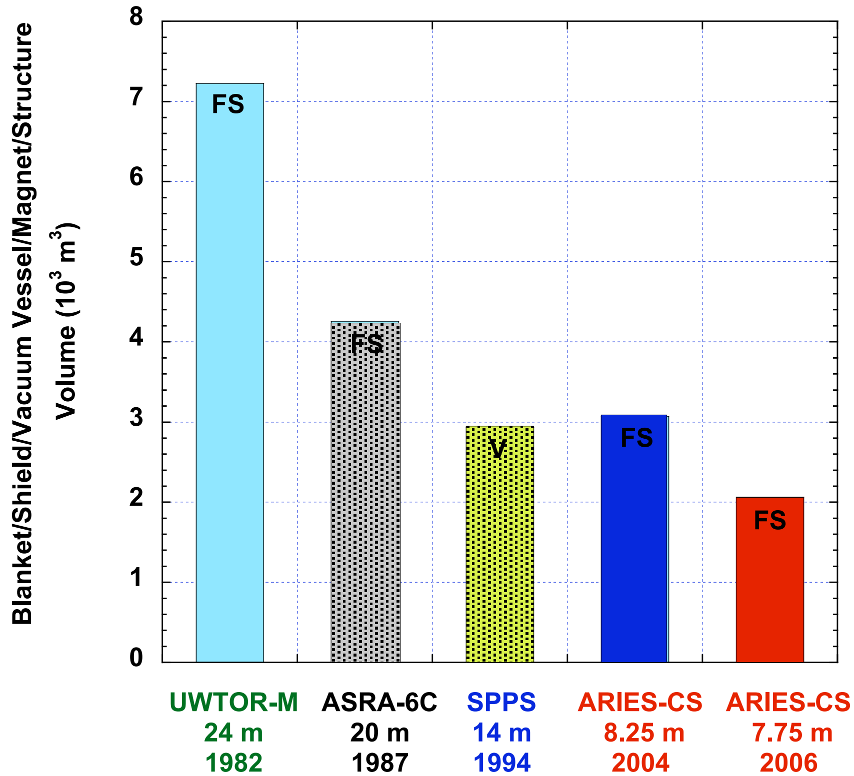
| | |
|---|---|
| **Peak NWL** | **5.3 MW/m$^2$** |
| **Average NWL** | **2.6 MW/m$^2$** |
| **Peak to Average NWL** | **2** |
| **Overall TBR** | **1.1** |
| **FW/blanket Lifetime** | **3 FPY** |
| **Shield/manifold/VV/magnet Lifetime** | **40 FPY** |
| **Overall Energy Multiplication** | **1.16** |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

# ARIES-CS Major Radius Approaches R of Advanced Tokamaks




Well optimized radial build along with advanced physics and technologies helped reduce ARIES-CS size

# ARIES Project Committed to Radwaste Minimization

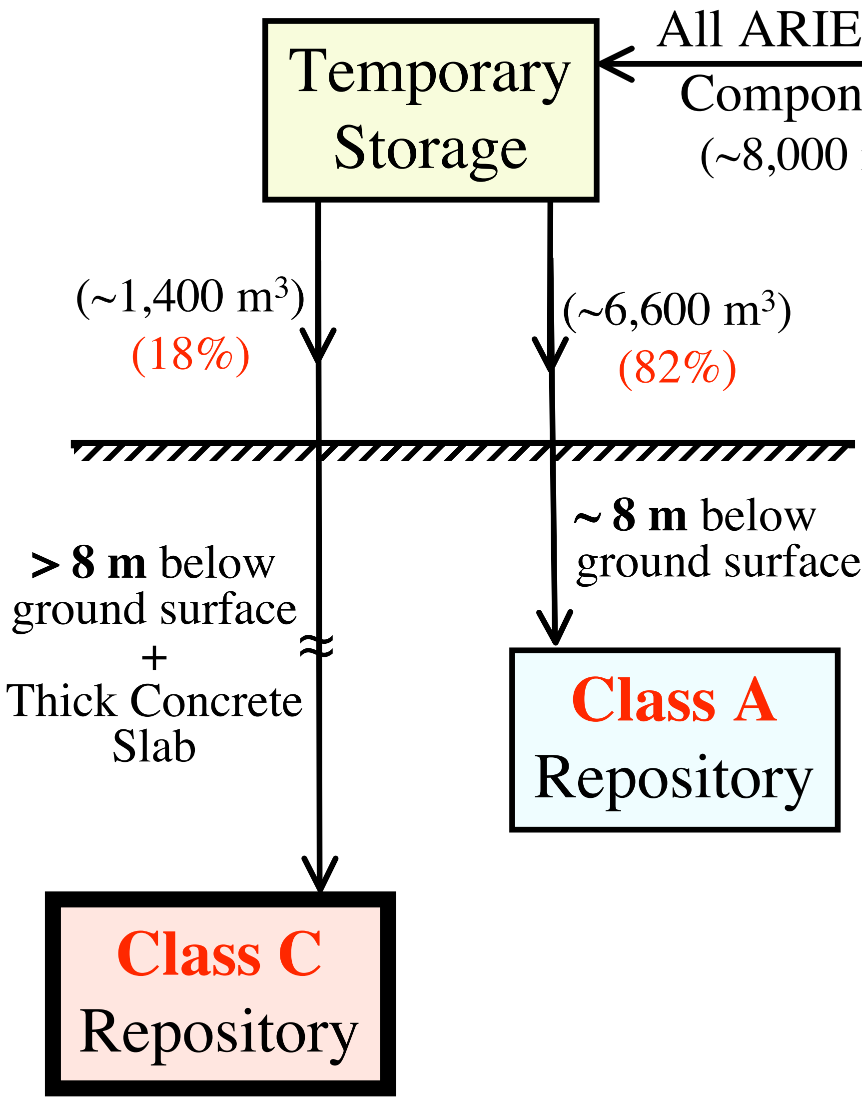


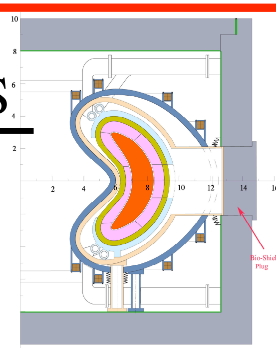

Stellarator waste volume dropped by factor of 3 over 25 y study period

* Actual volumes (not compacted, no replacements).

# Activation and Environmental Issues

# ARIES-CS Generates Only Low-Level Waste

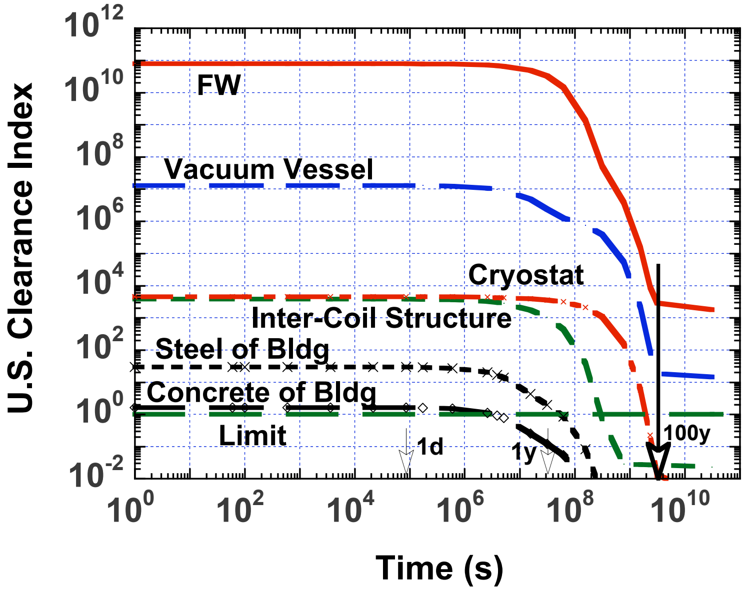


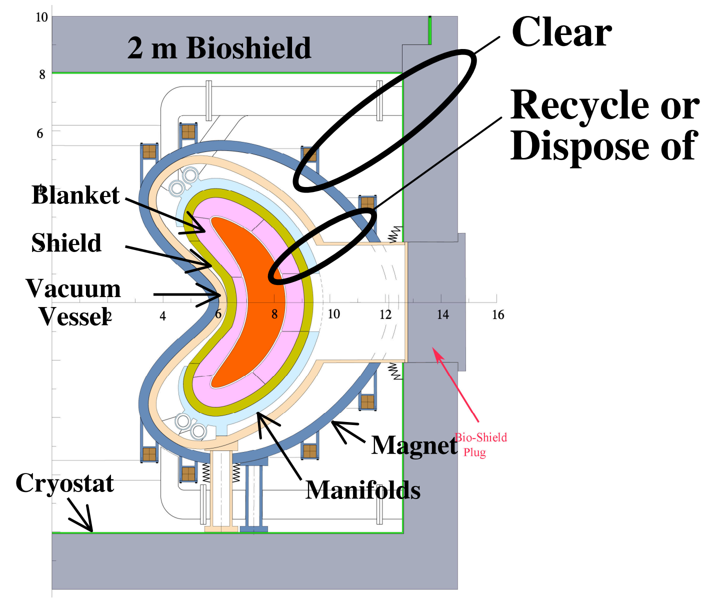



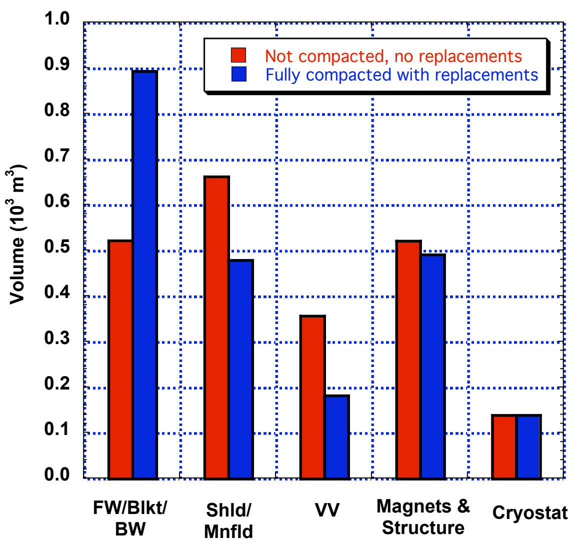
Least Hazardous Type of Waste

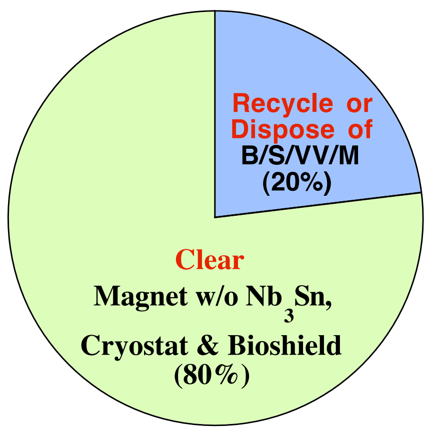
| | Class C LLW | Class A LLW | Could be Cleared? |
|---|---|---|---|
| FW/Blkt/BW | √ | | no |
| Shield/Manifolds | √ | | no |
| Vacuum Vessel | | √ | no |
| Magnet: | | | |
| $Nb_3Sn$ | √ | | no |
| Cu Stabilizer | | √ | √ |
| JK2LB Steel | | √ | √ |
| Insulator | | √ | √ |
| Cryostat | | √ | √ |
|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

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

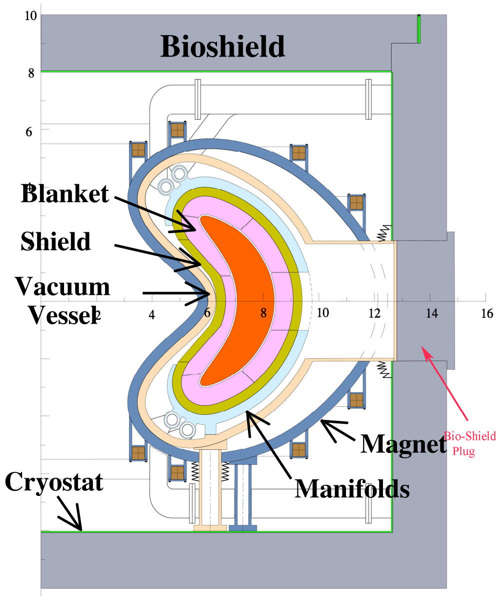


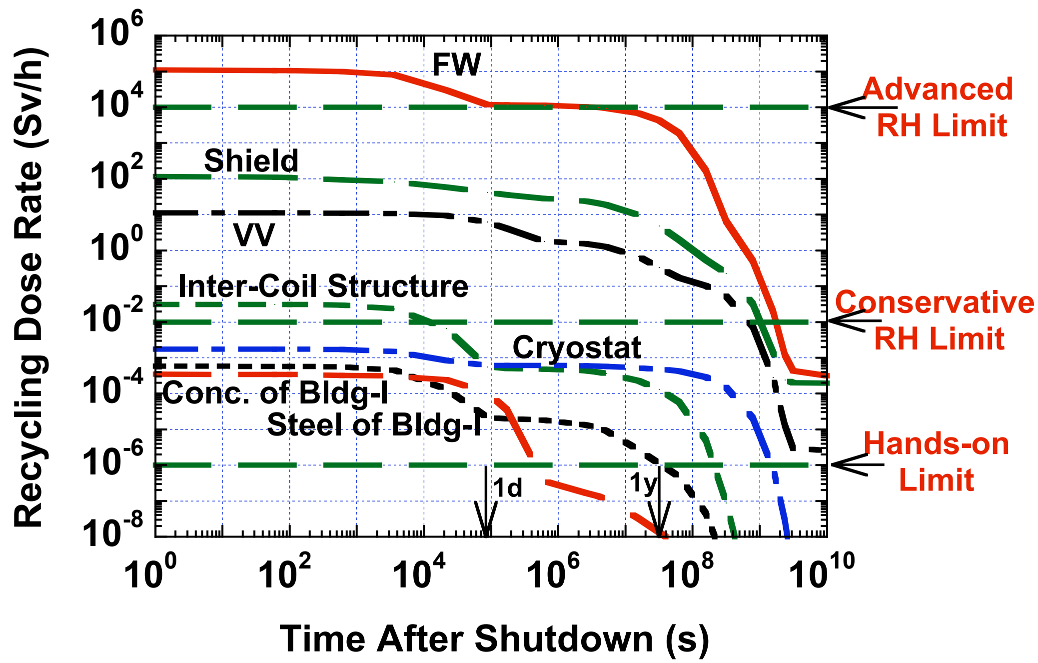



# All ARIES-CS Components can be Recycled in 1-2 y Using Advanced and Conventional RH Equipment



# Conclusions

- Novel shielding 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:
  - 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.