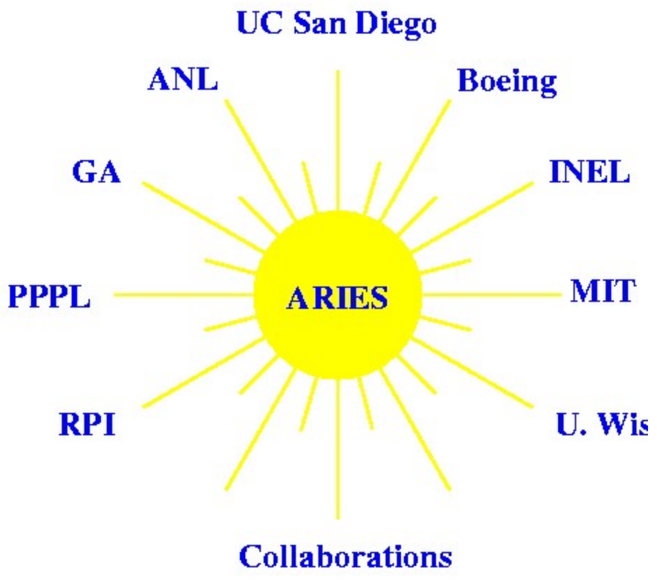
ARIES-AT: An Advanced Tokamak, Advanced Technology Fusion Power Plant

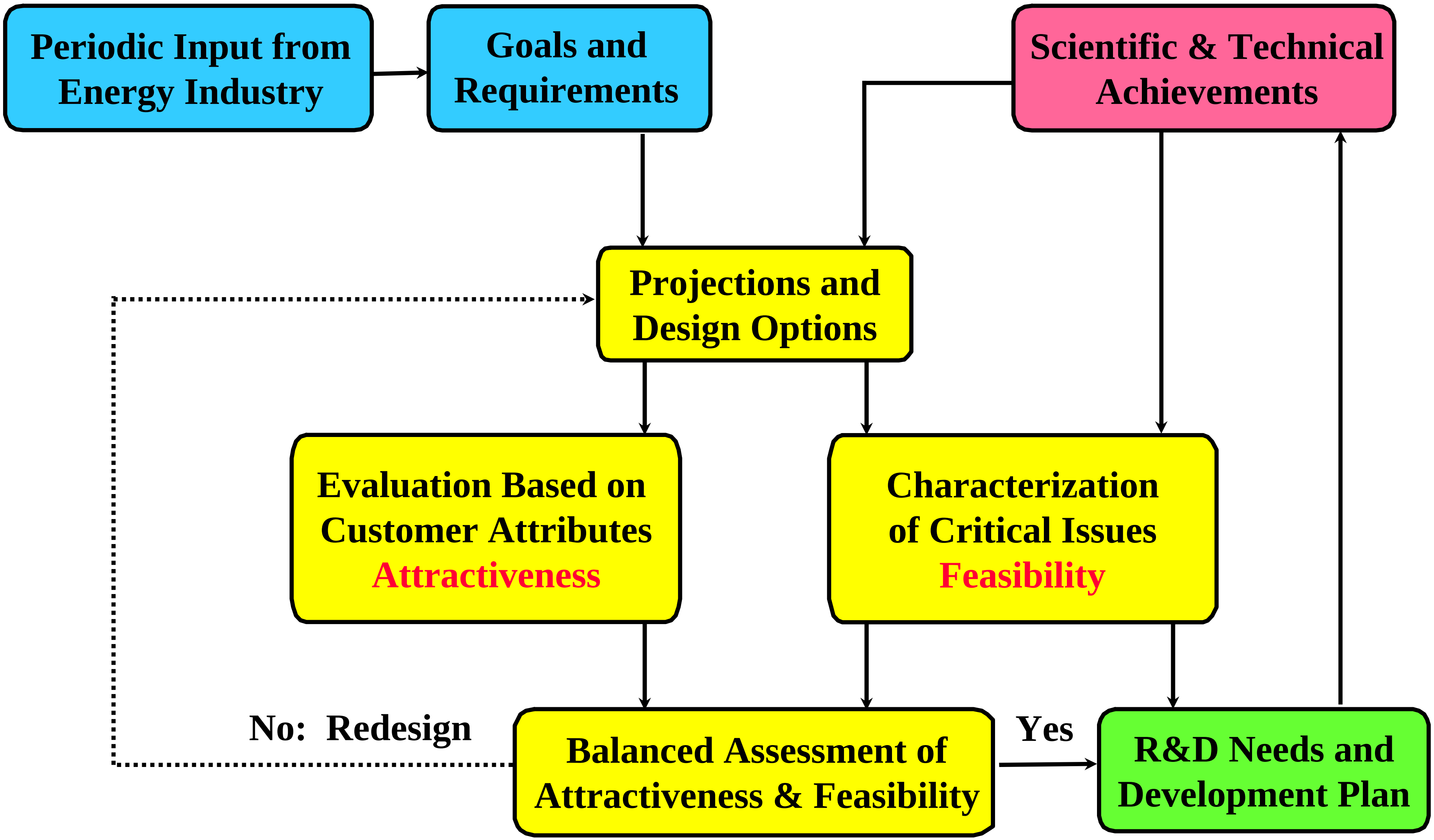
Farrokh Najmabadi
University of California, San Diego,
La Jolla, CA, United States of America

9th Course on Technology of Fusion Reactors
26 July – 1 August 2004
Erice Italy



Electronic Copy: **ARIES Web Site: http://aries.ucsd.edu/PUBLIC**

ARIES Research Framework: Identify Key R&D Issues and Provide a Vision for Fusion Research



ARIES Designs Are Developed Based on a Reasonable Extrapolation of Physics & Technology

ARIES Rules

- Plasma regimes of operation are optimized based on latest experimental achievements and/or “well-founded” theoretical predictions.
- Engineering system is based on “evolution” of present-day technologies, *i.e.*, they should be available at least in small samples now. Only learning-curve cost credits are assumed in costing the system components.

Optimization involves trade-off among Physics and Engineering constraints and parameters

- Trade-off between vertical stability and plasma shape (and β) and fusion core configuration and blanket thickness.
- Trade-off between plasma edge condition and plasma facing components capabilities
- ...

Customer Requirements

Top-Level Requirements for Fusion Power Plants Was Developed in Consultation with US Industry

Public Acceptance:

- No public evacuation plan is required: total dose < 1 rem at site boundary;
- Generated waste can be returned to environment or recycled in less than a few hundred years (not geological time-scale);
- No disturbance of public's day-to-day activities;
- No exposure of workers to a higher risk than other power plants;

Reliable Power Source:

- Closed tritium fuel cycle on site;
- Ability to operate at partial load conditions (50% of full power);
- Ability to maintain power core (availability > 80%);
- Ability to operate reliably with < 0.1 major unscheduled shut-down per year.

- **Economic Competitiveness:** Above requirements must be achieved <u>simultaneously</u> and consistent with a competitive life-cycle cost of electricity.

Directions for Optimization

Translation of Requirements to GOALS for Fusion Power Plants

Requirements:

- **Have an economically competitive life-cycle cost of electricity:**
  - Low recirculating power (Increase plasma Q, …);
  - High power density (Increase $P_f \sim \beta^2 B_T^4$, …)
  - High thermal conversion efficiency;
  - Less-expensive systems.

COE has a "hyperbolic" dependence ($\propto$ 1/x) and improvements "saturate" after certain limit

- **Gain Public acceptance by having excellent safety and environmental characteristics:**
  - Use low-activation and low toxicity materials and care in design.
- **Have operational reliability and high availability:**
  - Ease of maintenance
  - Design margins, and extensive R&D.
- **Acceptable cost of development.**

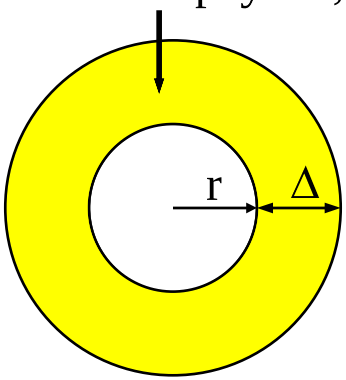
Larger extrapolation from present

Stay close to present-day

There Is Little Economic Benefit for Operating Beyond ~ 5 MW/m² of Wall Load (for 1000MWe)

- Simple analysis for a cylindrical plasma with length L:

What we pay for, V_{FPC}



Wall loading $I_w \propto 1/r$

Δ is set by neutron mfp

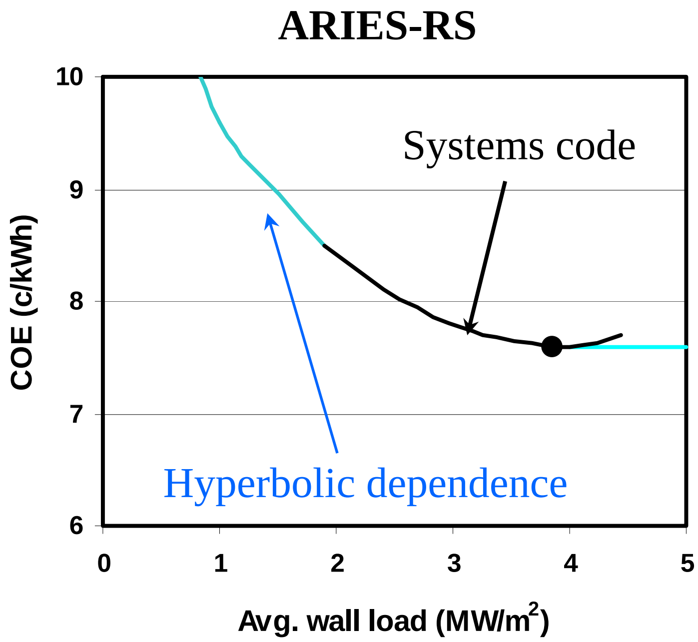
$V_{FPC} = \pi L\,(2r\Delta + \Delta^2)$

For $r >> \Delta$, $V_{FPC} \cong 2\pi L r \Delta \propto 1/I_w$

For $r << \Delta$, $V_{FPC} \cong 2\pi L \Delta^2 \cong$ const.

Hyperbolic dependence

- "Knee of the curve" is at $r \cong \Delta$



- Physics & Engineering constraints cause departure from geometrical dependence *e.g.*, high field needed for high load increases TF cost.
- ARIES-AT optimizes at lower wall loading because of high efficiency.

Continuity of ARIES research has led to the progressive refinement of research

Improved Physics

ARIES-I (1990):

- Trade-off of β with bootstrap
- High-field magnets to compensate for low β

Need high β equilibria with high bootstrap

ARIES-II/IV, 2nd Stability (1992):

- High β only with too much bootstrap
- Marginal reduction in current-drive power

Need high β equilibria with aligned bootstrap

ARIES-RS, reverse shear (1996):

- Improvement in β and current-drive power
- Approaching COE insensitive of power density

Better bootstrap alignment

More detailed physics

ARIES-AT, reverse shear (2000):

- Approaching COE insensitive of current-drive
- High β is used to reduce toroidal field

Evolution of ARIES Designs

	1st Stability, Nb_3Sn Tech.	High-Field Option	Reverse Shear Option	
	ARIES-I'	ARIES-I	ARIES-RS	ARIES-AT
Major radius (m)	8.0	6.75	5.5	5.2
β (β_N)	2% (2.9)	2% (3.0)	5% (4.8)	9.2% (5.4)
Peak field (T)	16	19	16	11.5
Avg. Wall Load (MW/m^2)	1.5	2.5	4	3.3
Current-driver power (MW)	237	202	81	36
Recirculating Power Fraction	0.29	0.28	0.17	0.14
Thermal efficiency	0.46	0.49	0.46	0.59
Cost of Electricity (c/kWh)	10	8.2	7.5	5

Approaching COE insensitive of power density

Approaching COE insensitive of current drive

ARIES-AT
Physics Analysis

ARIES-AT: Physics Highlights

- We used the lessons learned in ARIES-ST optimization to reach a higher performance plasma;
  - Using > 99% flux surface from free-boundary plasma equilibria rather than 95% flux surface used in ARIES-RS leads to larger elongation and triangularity and higher stable β.
- ARIES-AT blanket allows vertical stabilizing shell closer to the plasma, leading to higher elongation and higher β.
- Detailed stability analysis indicated that H–mode pressure & current profiles and X-point improves ballooning stability.
- A kink stability shell (τ = 10 ms), 1 cm of tungsten behind the blanket, is utilized to keep the power requirements for $n = 1$ resistive wall mode feedback coil at a modest level.

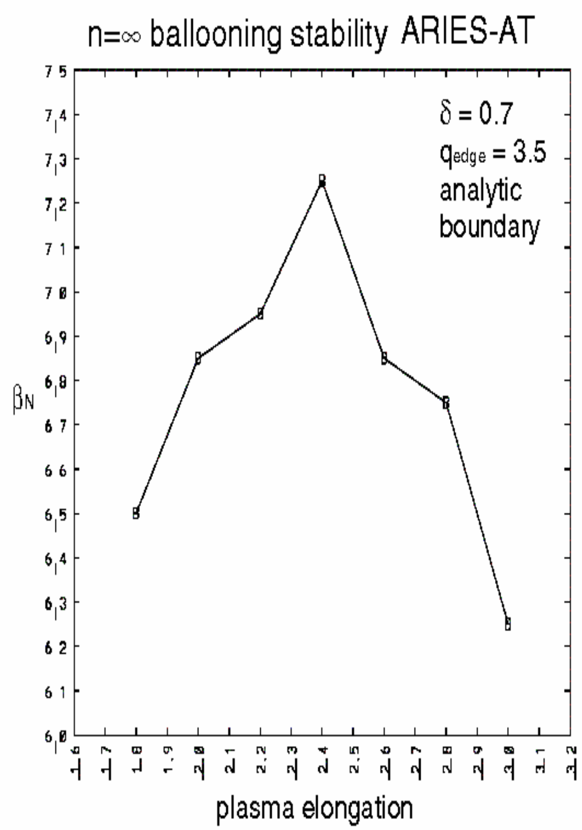
ARIES-AT: Physics Highlights

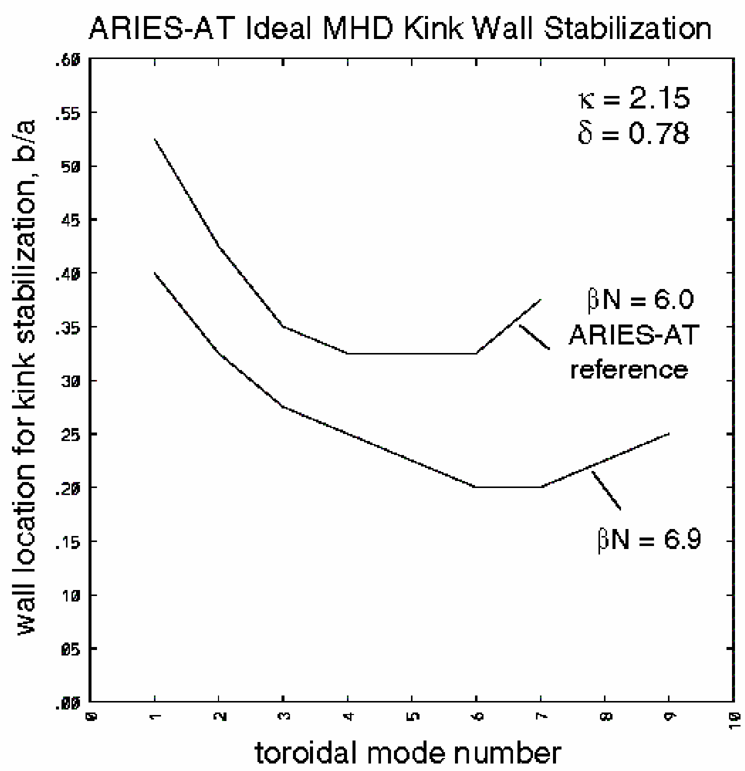
- We eliminated HHFW current drive and used only lower hybrid for off-axis current drive.
- Self-consistent physics-based transport simulations indicated the optimized pressure and current profiles can be sustained with a peaked density profile.
- A radiative divertor is utilized to keep the peak heat flux at the divertor at ~ 5 MW/m^2.
- Accessible fueling; No ripple losses; 0-D consistent startup; *etc*.

- As a whole, we performed detailed, self-consistent analysis of plasma MHD, current drive, transport, and divertor (using finite edge density, finite p′, impurity radiation, *etc.)*

The ARIES-AT Equilibrium is the Results of Extensive ideal MHD Stability Analysis

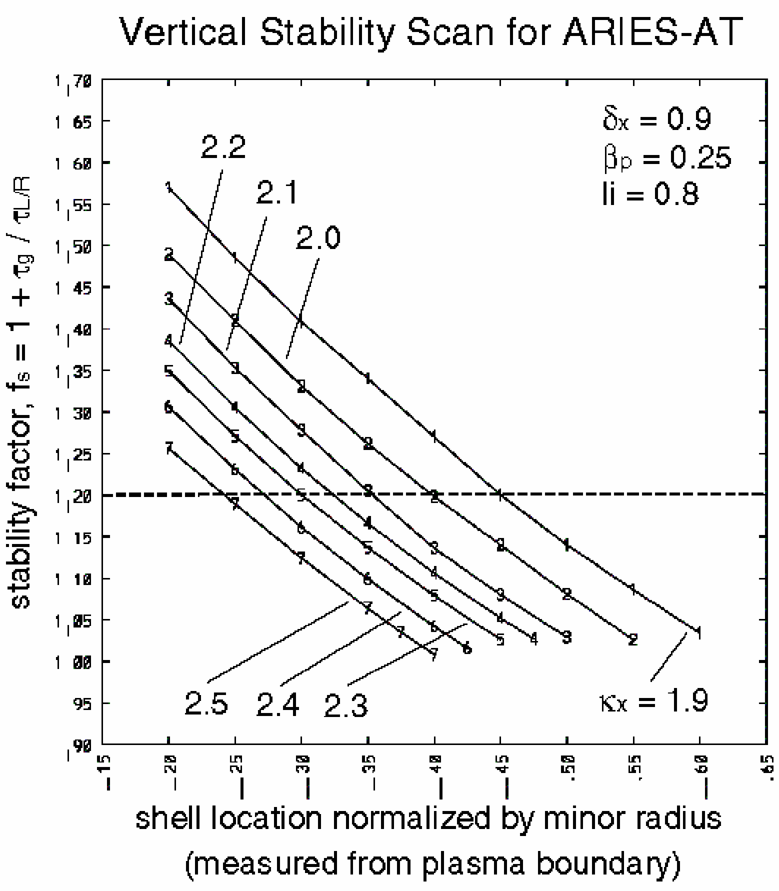
- Pressure profiles scans show the interplay between plasma β and bootstrap alignment – optimum profiles are NOT at the highest β.



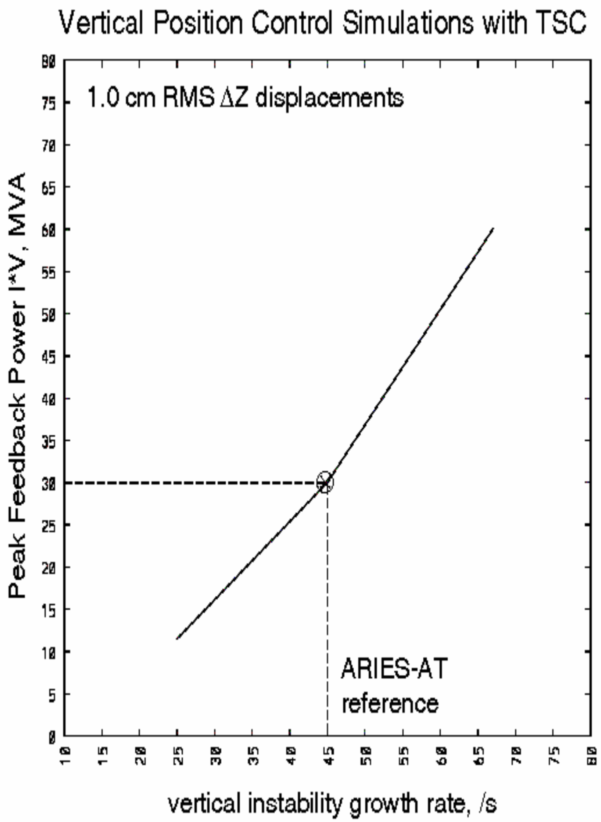


- Intermediate n kink sets the wall location
- ARIES-AT plasma operates at 90% of theoretical β limit.

Vertical Stability and Control is a Critical Physics/Engineering Interface



- *TSC* nonlinear dynamic simulations of vertical stability and feedback control show the tradeoff of power and accessible plasmas



- ARIES-AT elongation of $\kappa = 2.2$ is consistent with allowed stabilizer location

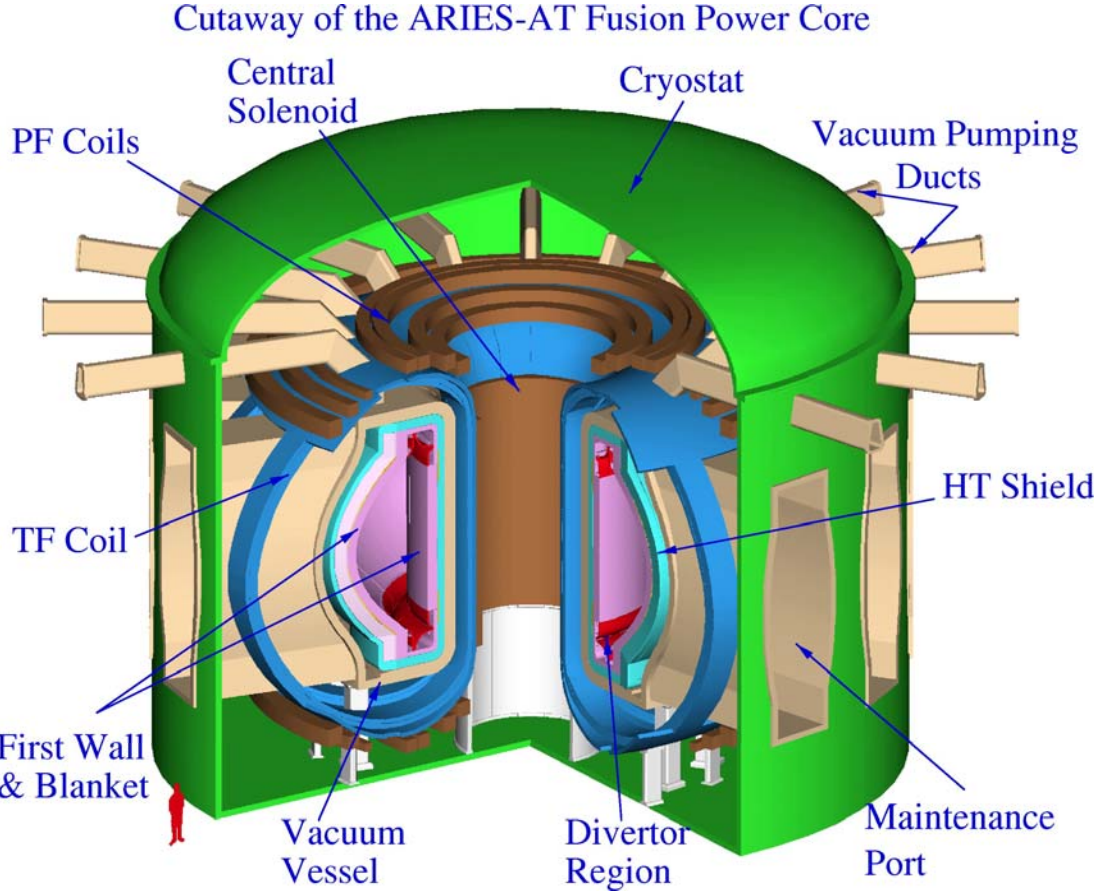
Major Plasma Parameters of ARIES-AT

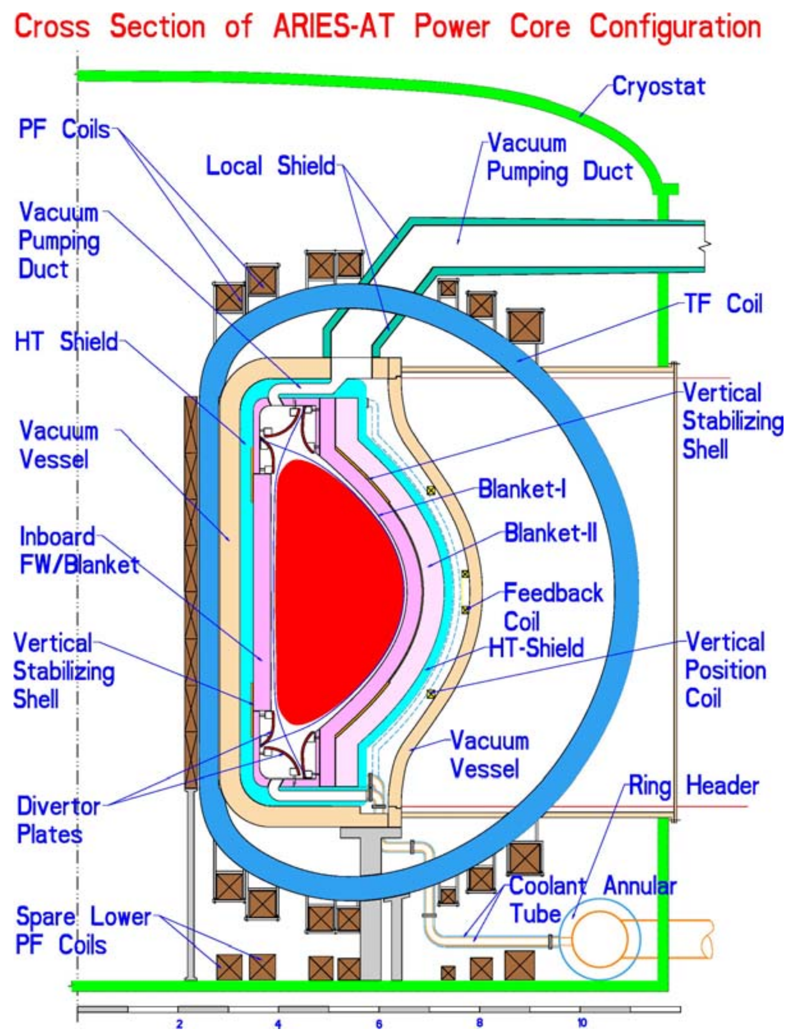
Aspect ratio	4.0
Major toroidal radius (m)	5.2
Plasma minor radius (m)	1.3
Plasma elongation (κ_x)	2.2
Plasma triangularity (δ_x)	0.84
Toroidal β ‡	9.2%
Normalize β_N ‡	5.4
Electron density (10^{20} m^{-3})	2.3
ITER-89P scaling multiplier	2.6
Plasma current	13
On-axis toroidal field (T)	6
Current-drive power to plasma (MW)	36

‡ ARIES-AT plasma operates at 90% of maximum theoretical limit

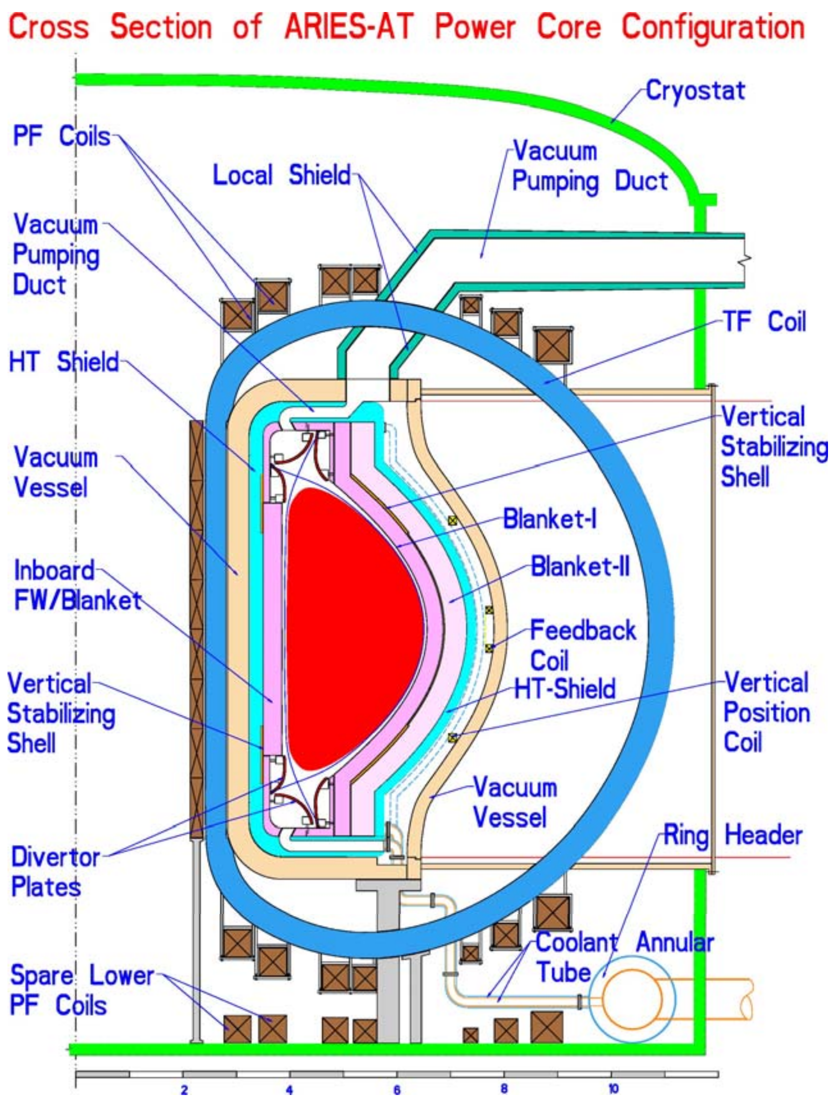
ARIES-AT
Engineering Analysis

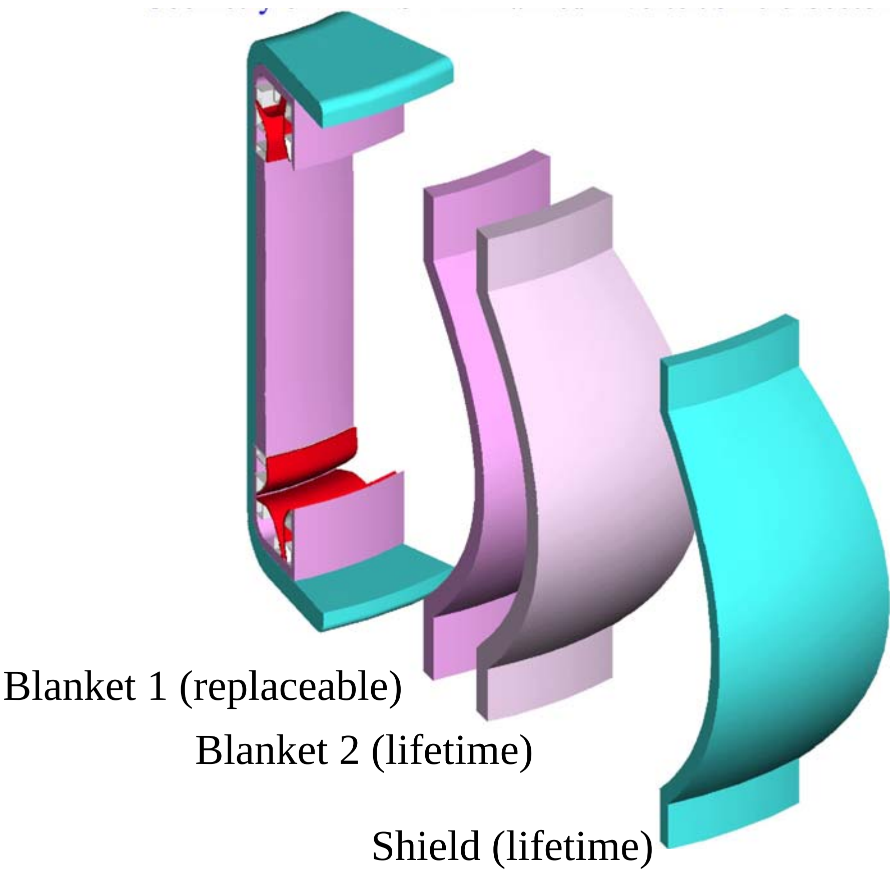
ARIES-AT Fusion Core





Fusion Core Is Segmented to Minimize the Rad-Waste

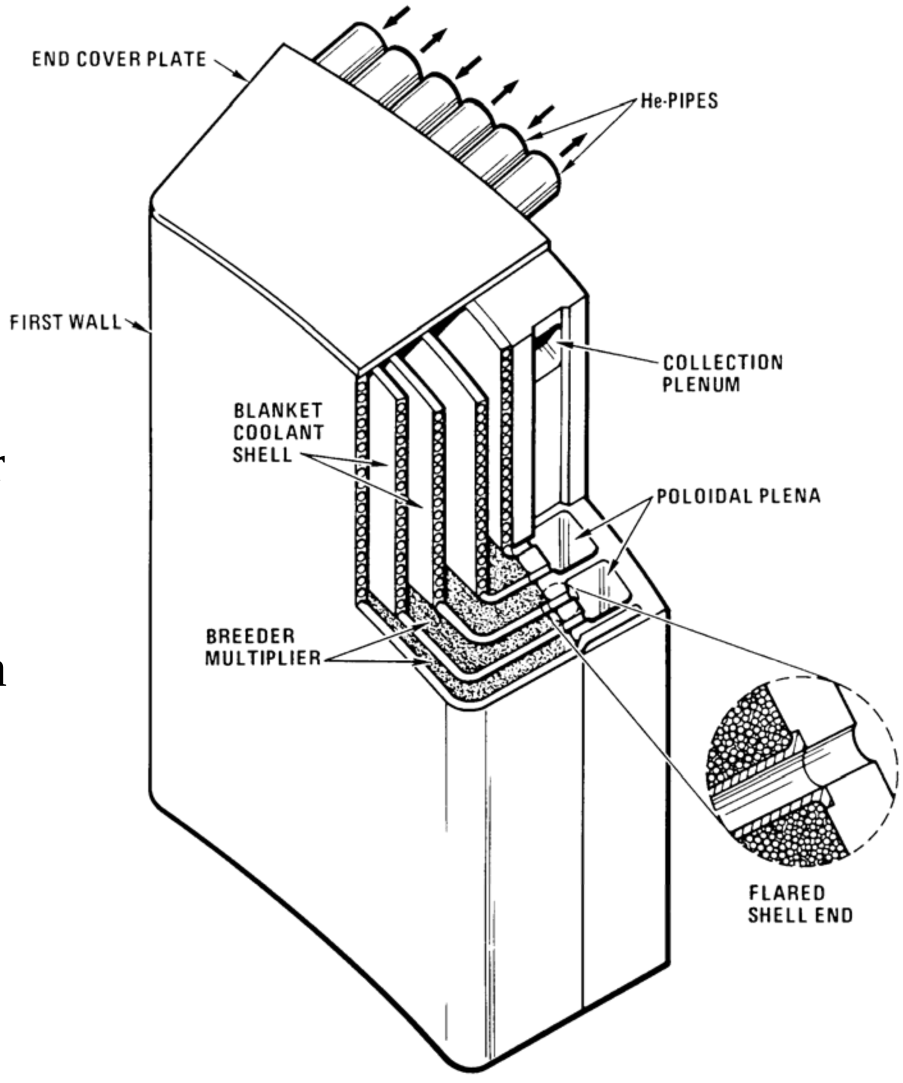




- Only "blanket-1" and divertors are replaced every 5 years

ARIES-I Introduced SiC Composites as A High-Performance Structural Material for Fusion

- Excellent safety & environmental characteristics (very low activation and very low afterheat).
- High performance due to high strength at high temperatures (>1000°C).
- Large world-wide program in SiC:
  * New SiC composite fibers with proper stoichiometry and small O content.
  * New manufacturing techniques based on polymer infiltration results in much improved performance and cheaper components.
  * Recent results show composite thermal conductivity (under irradiation) close to 15 W/mK which was used for ARIES-I.



Continuity of ARIES research has led to the progressive refinement of research

Improved Blanket Technology

ARIES-I:
- SiC composite with solid breeders
- Advanced Rankine cycle

Many issues with solid breeders; Rankine cycle efficiency saturated at high temperature

Starlite & ARIES-RS:
- Li-cooled vanadium
- Insulating coating

Max. coolant temperature limited by maximum structure temperature

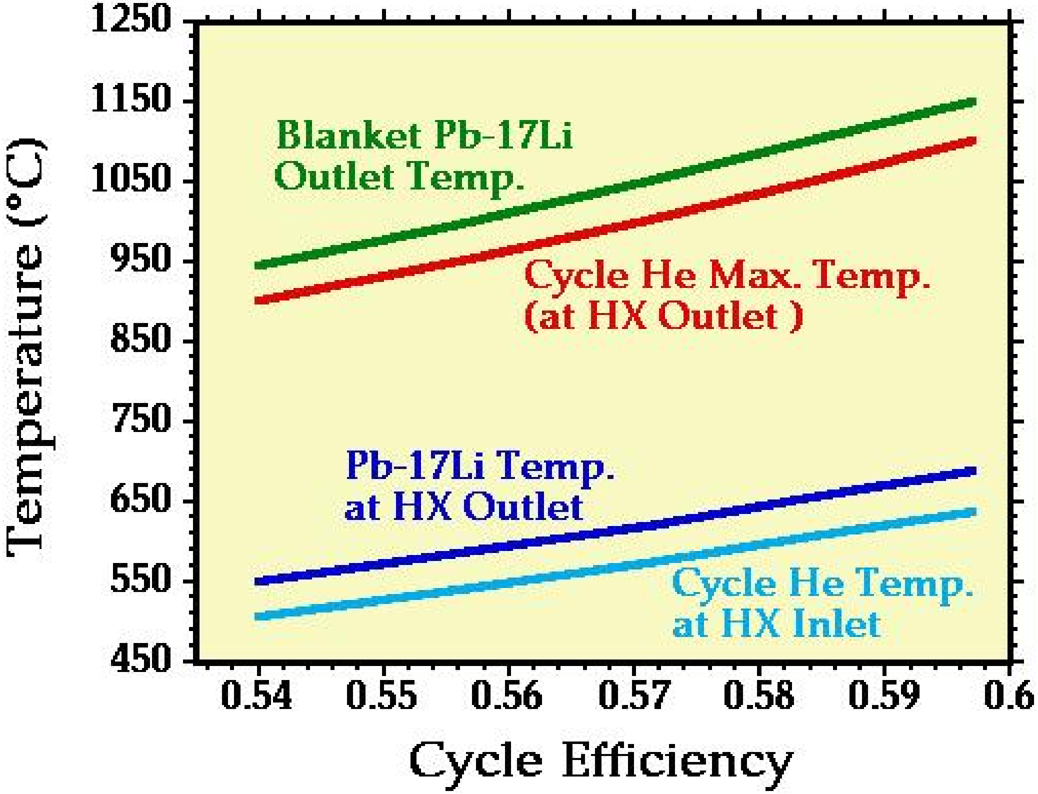
ARIES-ST:
- Dual-cooled ferritic steel with SiC inserts
- Advanced Brayton Cycle at $\geq 650\ ^{o}C$

High efficiency with Brayton cycle at high temperature

ARIES-AT:
- LiPb-cooled SiC composite
- Advanced Brayton cycle with $\eta = 59\%$

Advanced Brayton Cycle Parameters Based on Present or Near Term Technology Evolved with Expert Input from General Atomics*

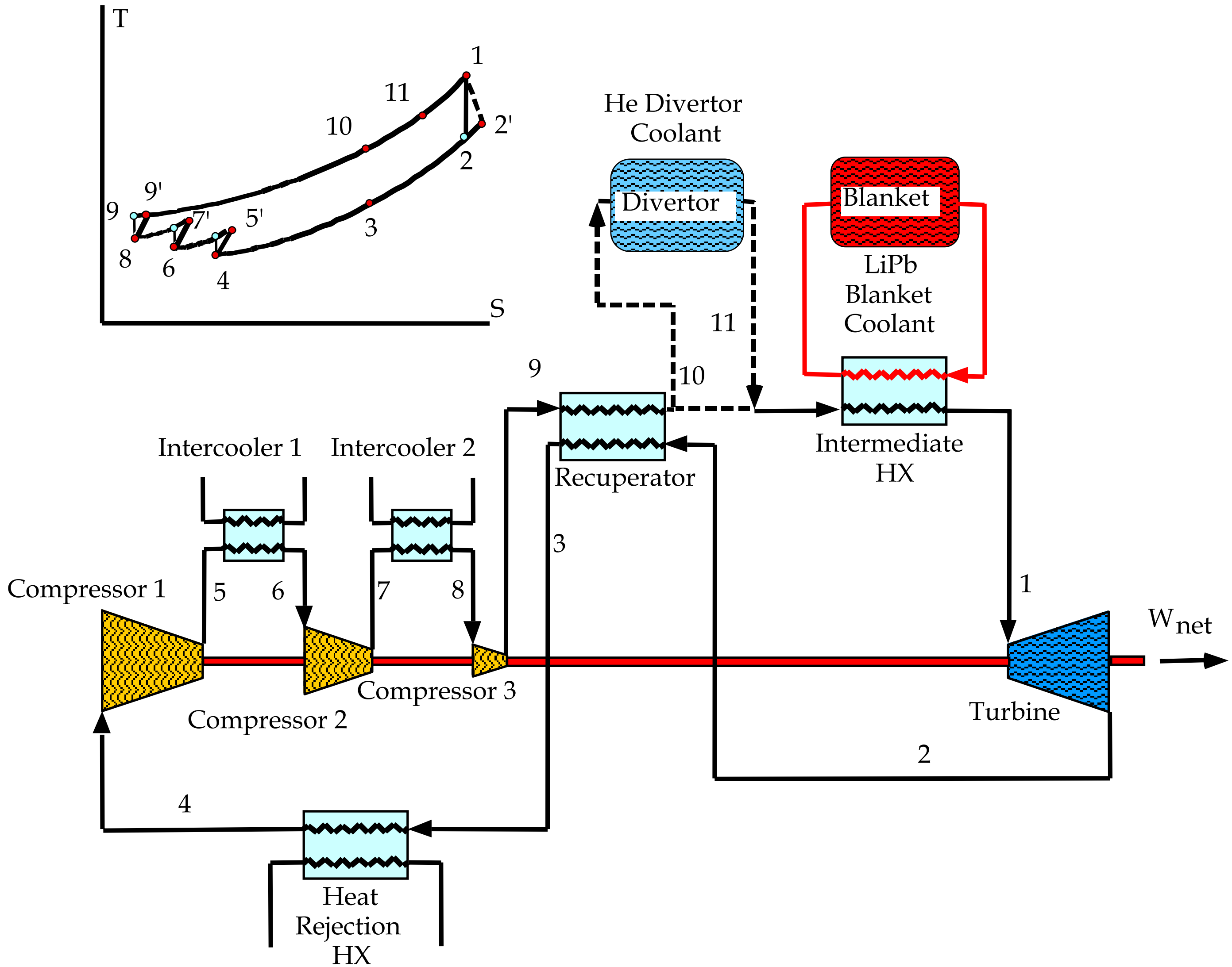
- Min. He Temp. in cycle (heat sink) = 35°C
- 3-stage compression with 2 inter-coolers
- Turbine efficiency = 0.93
- Compressor efficiency = 0.88
- Recuperator effectiveness (advanced design) = 0.96
- Cycle He fractional ΔP = 0.03
- Intermediate Heat Exchanger
  - Effectiveness = 0.9
  - $(mCp)_{He}/(mCp)_{Pb\text{-}17Li} = 1$



➢ Key improvement is the development of cheap, high-efficiency recuperators.

*R. Schleicher, A. R. Raffray, C. P. Wong, "An Assessment of the Brayton Cycle for High Performance Power Plant," 14th ANS Topical Meeting on Technology of Fusion Energy, October 15-19, 2000, Park City Utah

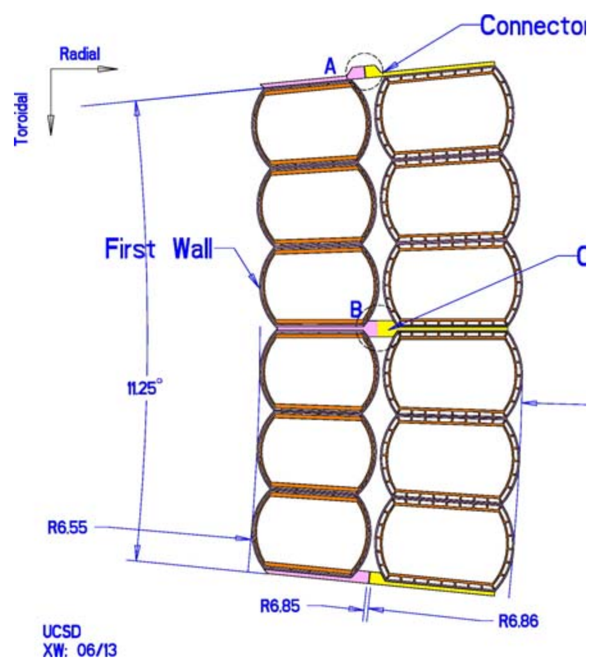
Recent Advances in Brayton Cycle Leads to Power Cycles With High Efficiency

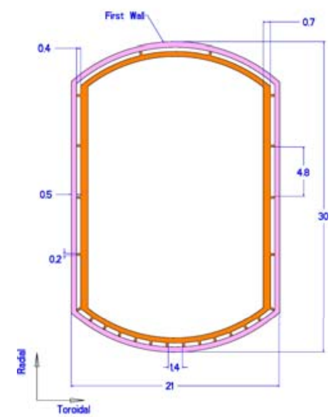


ARIES-AT: SiC Composite Blankets

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1,100°C) while keeping SiC structure temperature below 1,000°C leading to a high thermal efficiency of ~ 60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
- LiPb-cooled SiC composite divertor is capable of 5 MW/m^2 of heat load.

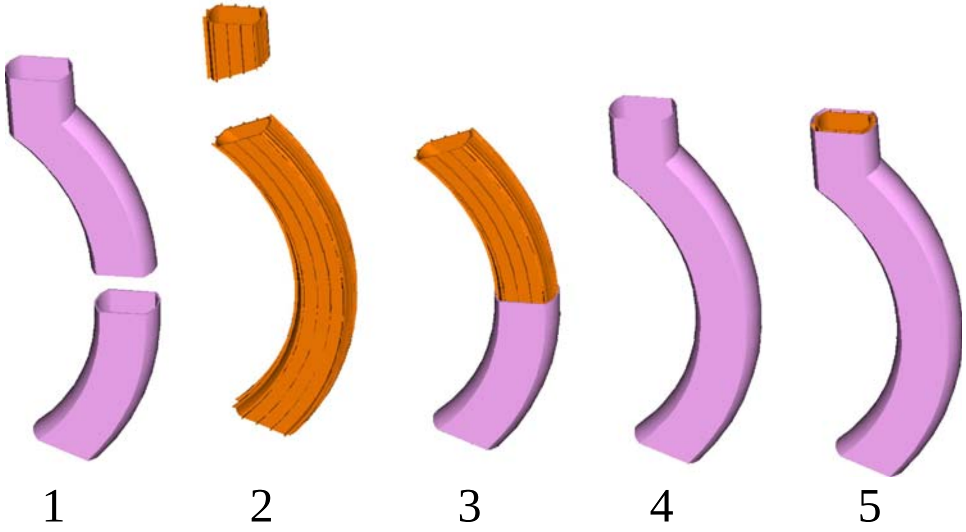
Outboard blanket & first wall



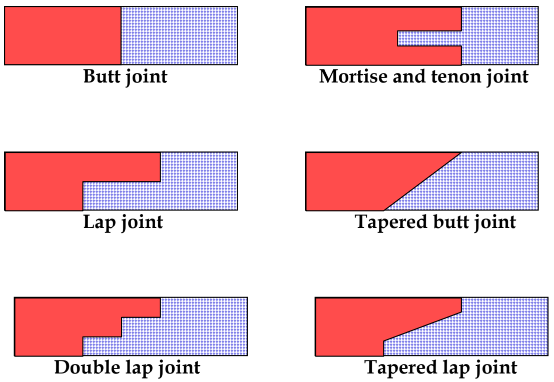


Develop Plausible Fabrication Procedure and Minimize Joints in High Irradiation Region

1. Manufacture separate halves of the SiC_f/SiC poloidal module by SiC_f weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process;
2. Manufacture curved section of inner shell in one piece by SiC_f weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process;
3. Slide each outer shell half over the free-floating inner shell;
4. Braze the two half outer shells together at the midplane;
5. Insert short straight sections of inner shell at each end;

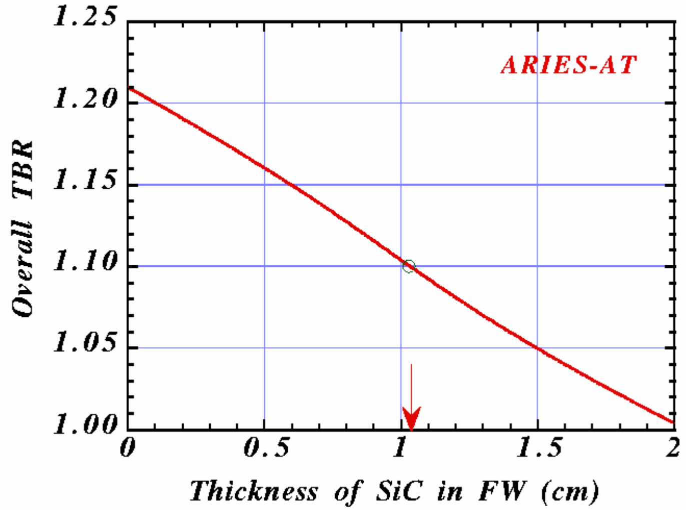


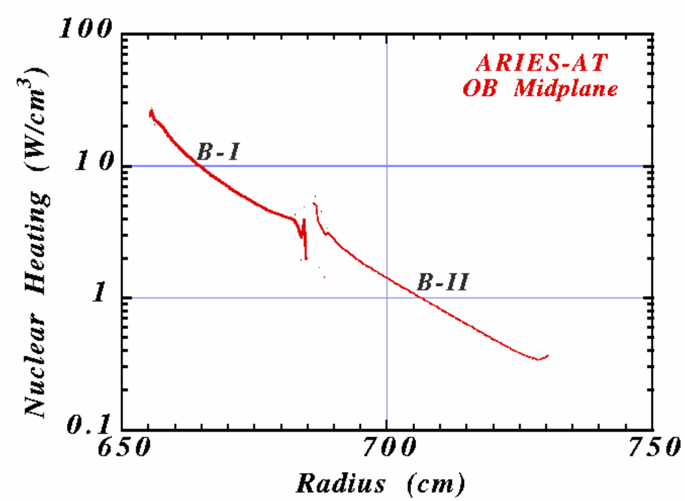
Brazing procedure selected for reliable joint contact area



Multi-Dimensional Neutronics Analysis to Calculate Tritium Breeding Ratio and Heat Generation Profiles

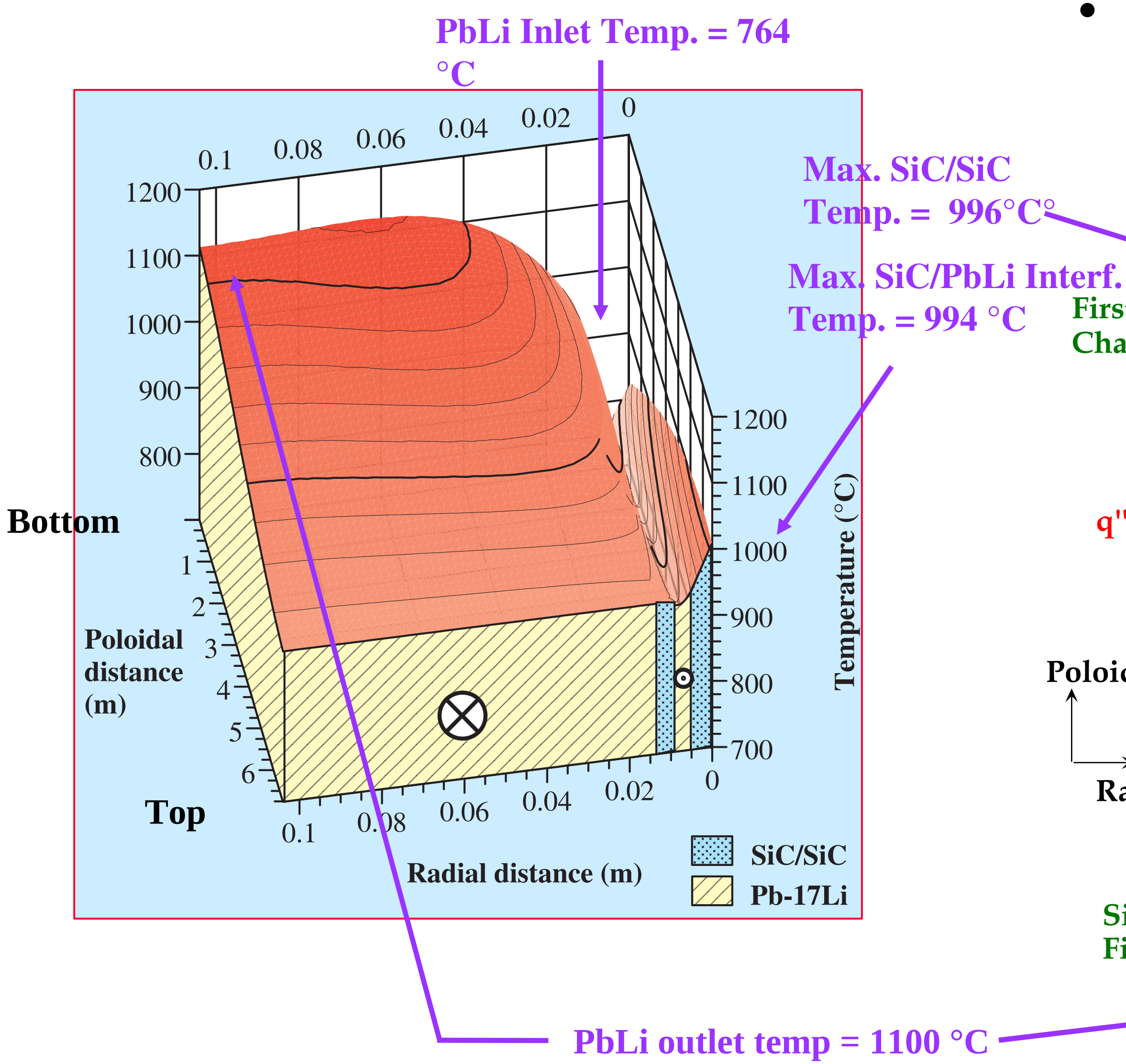
- Latest data and code
- 3-D tritium breeding > 1.1 to account for uncertainties
- Blanket configuration and zone thicknesses adjusted accordingly
- Blanket volumetric heat generation profiles used for thermal-hydraulic analyses

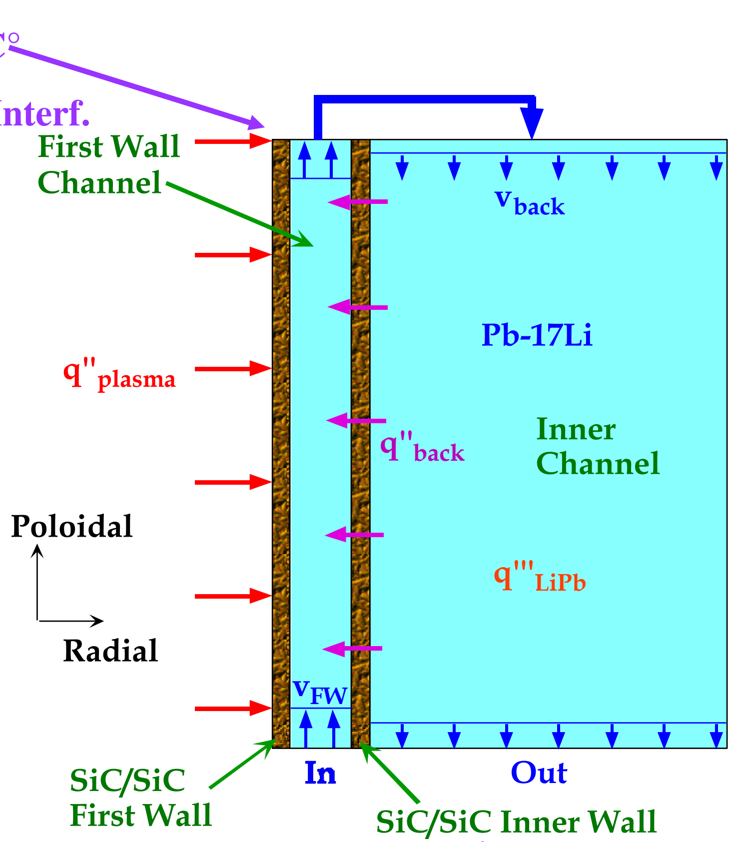




Innovative Design Results in a LiPb Outlet Temperature of 1,100ºC While Keeping SiC Temperature Below 1,000ºC

- Two-pass PbLi flow,
  first pass to cool SiC_f/SiC box
  second pass to superheat PbLi





Details of Thermal Analysis of ARIES-AT First Wall Channel and Inner Channel

Model Description:

- Assume MHD-flow-laminarization effect
- Use plasma heat flux poloidal profile
- Use volumetric heat generation poloidal and radial profiles
- Iterate for consistent boundary conditions for heat flux between Pb-17Li inner channel zone and first wall zone
- Calibration with ANSYS 2-D results

Parameters

- PbLi Inlet Temperature = 764 °C
- PbLi Outlet Temperature = 1,100 °C

Radial build (from plasma side:)

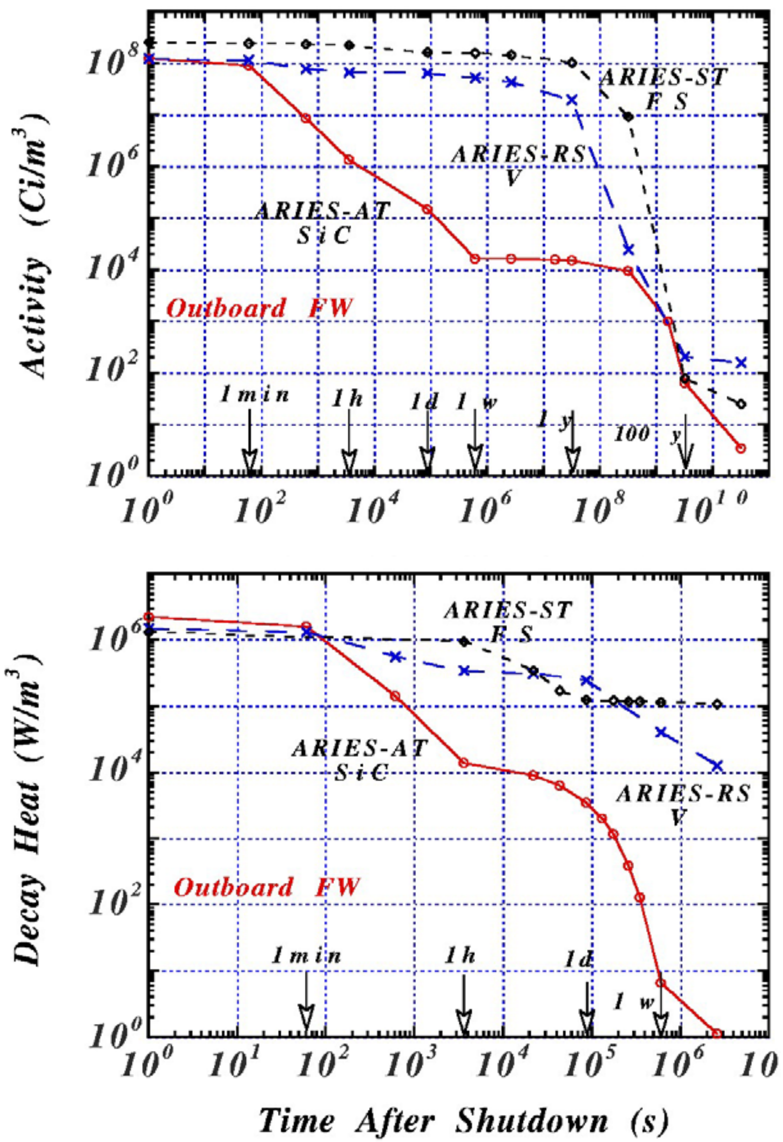
- CVD SiC Thickness = 1 mm
- SiC_f/SiC Thickness = 4 mm
  (SiC_f/SiC k = 20 W/m-K)
- PbLi Channel Thick. = 4 mm
- SiC/SiC Separator Thickness = 5 mm
  (SiC_f/SiC k = 6 W/m-K)

- PbLi velocity in FW Channel= 4.2 m/s
- PbLi velocity in inner Channel = 0.1 m/s

ARIES-AT Outboard Blanket Parameters

Number of Segments	32
Number of Modules per Segment	6
Module Poloidal Dimension	6.8 m
Average Module Toroidal Dimension	0.19 m
First Wall SiC_f/SiC Thickness	4 mm
First Wall CVD SiC Thickness	1 mm
First Wall Annular Channel Thickness	4 mm
Average Pb-17Li Velocity in First Wall	4.2 m/s
First Wall Channel Re	3.9×10^5
First Wall Channel Transverse Ha	4340
MHD Turbulent Transition Re	2.2×10^6
First Wall MHD Pressure Drop	0.19 MPa
Maximum SiC_f/SiC Temperature	996°C
Maximum CVD SiC Temperature	1,009 °C
Maximum Pb-17Li/SiC Interface Temperature	994°C
Average Pb-17Li Velocity in Inner Channel	0.11 m/s

Multi-Dimensional Neutronics Analysis was Performed to Calculate TBR, activities, & Heat Generation Profiles

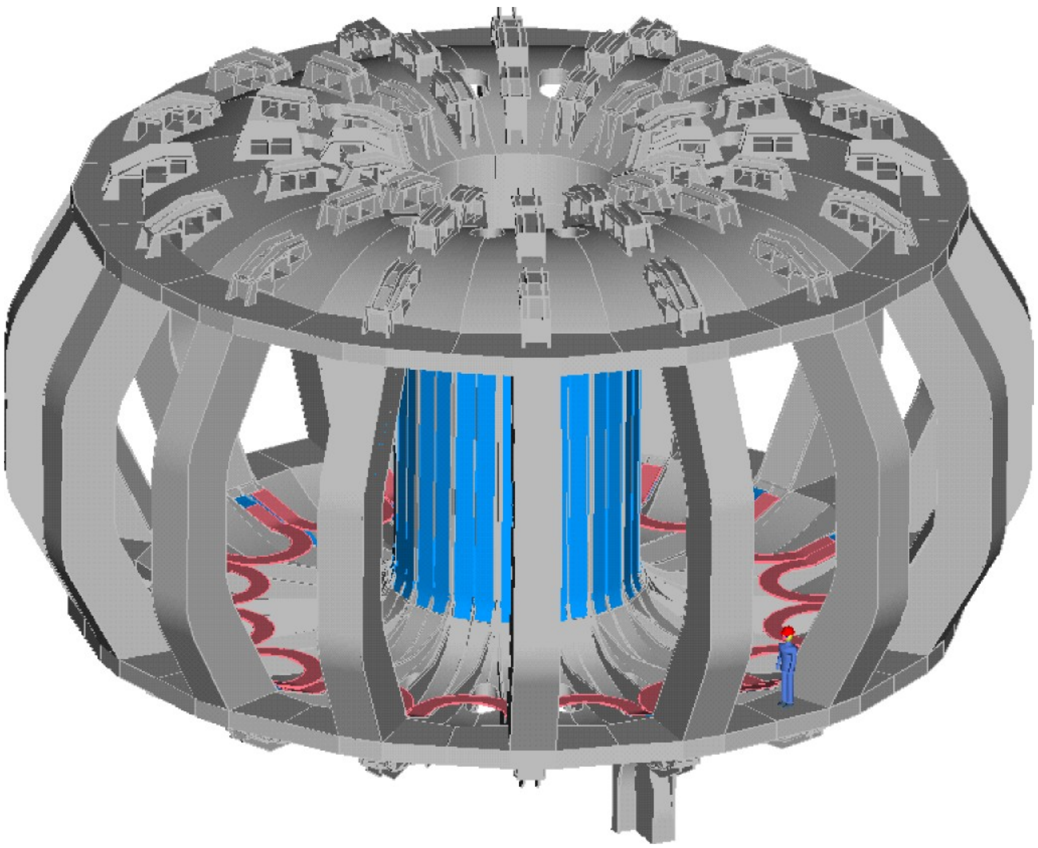


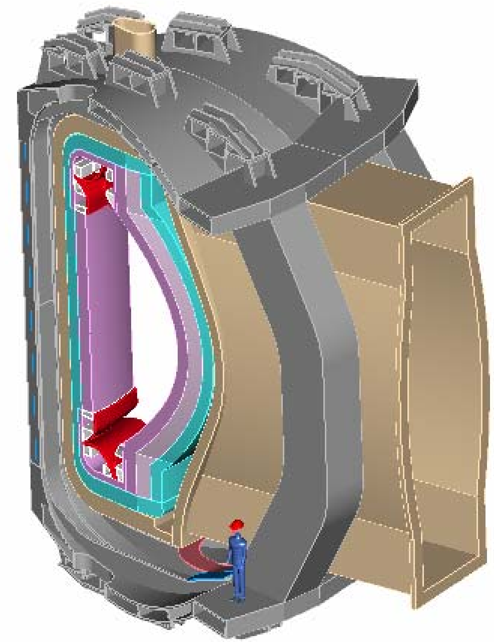
- Very low activation and afterheat Lead to excellent safety and environmental characteristics.
- All components qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.
- On-line removal of Po and Hg from LiPb coolant greatly improves the safety aspect of the system and is relatively straight forward.

Major Engineering Parameters of ARIES-AT

Fusion power (MW)	1,755
Energy Multiplication, M	1.1
Thermal Power (MW)	1,897
Peak/Avg. first wall heat flux (MW/m^2)	0.34/0.26
Peak/Avg. neutron wall load (MW/m^2)	4.9/3.3
LiPb coolant outlet temperature (°C)	1,100
Thermal efficiency	0.59
Gross electric power (MW)	1,136
Recirculating power fraction	0.14
Cost of electricity (c/kWh)	5

ARIES-AT Toroidal-Field Magnets





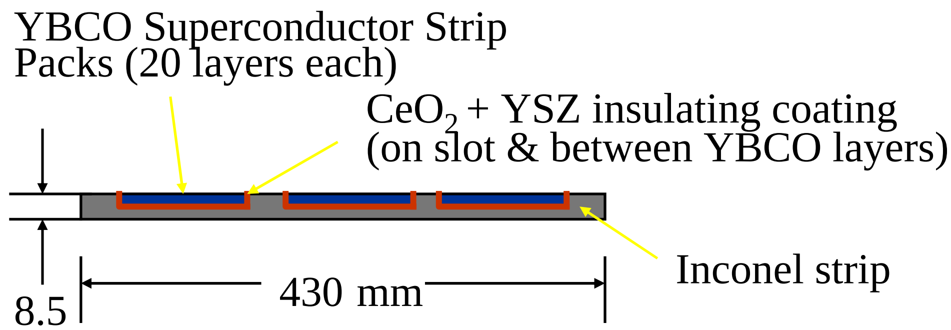
- On-axis toroidal field: 6 T
- Peak field at TF coil: 11.4 T

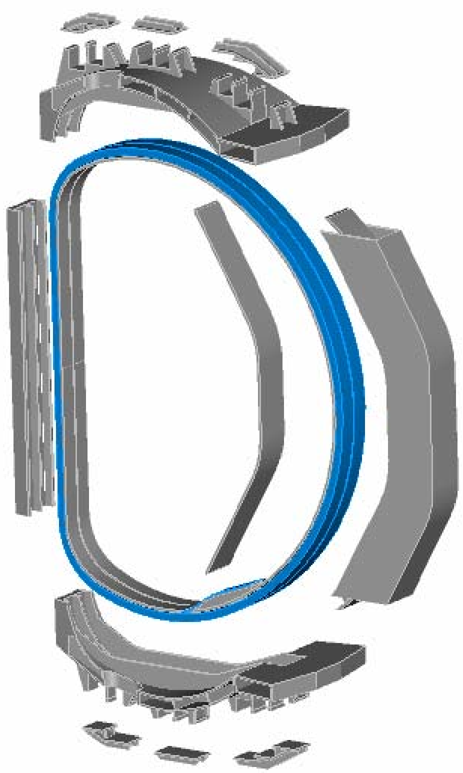
Use of High-Temperature Superconductors Simplifies the Magnet Systems

- ➢ HTS does not offer significant superconducting property advantages over low temperature superconductors due to the low field and low overall current density in ARIES-AT

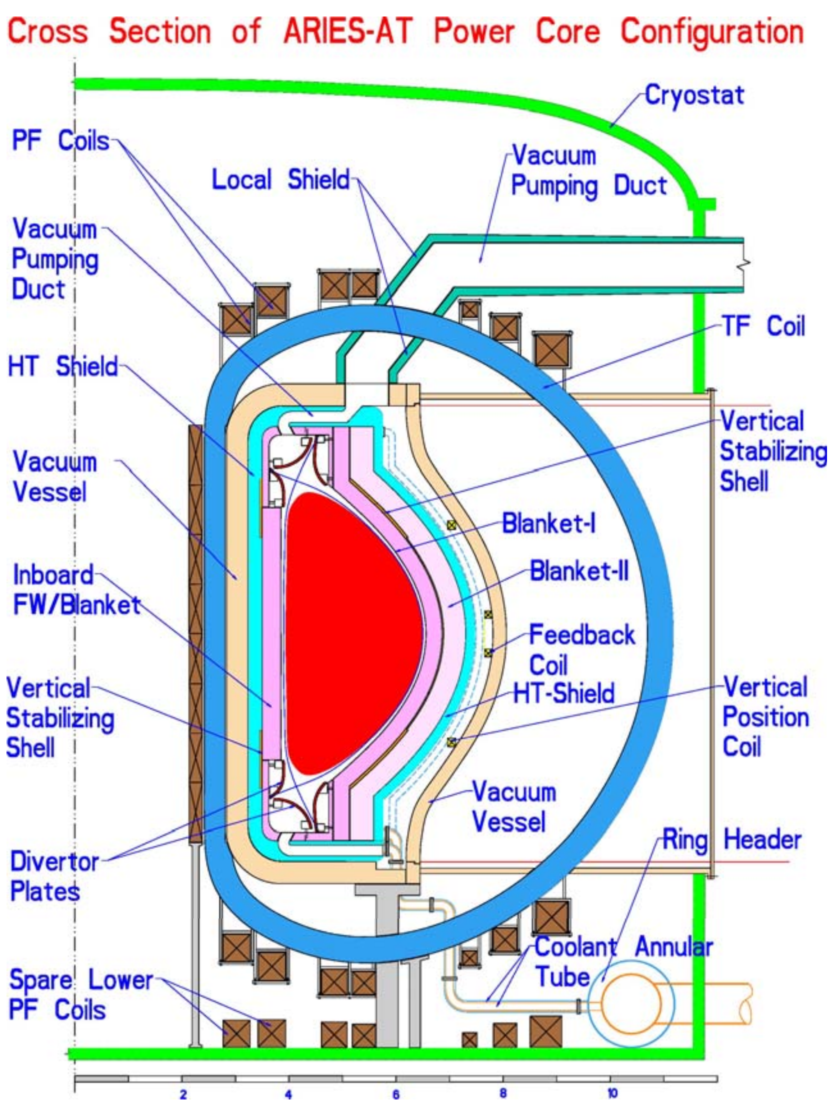
- ➢ HTS does offer operational advantages:
  - ∗ Higher temperature operation (even 77K), or dry magnets
  - ∗ Wide tapes deposited directly on the structure (less chance of energy dissipating events)
  - ∗ Reduced magnet protection concerns

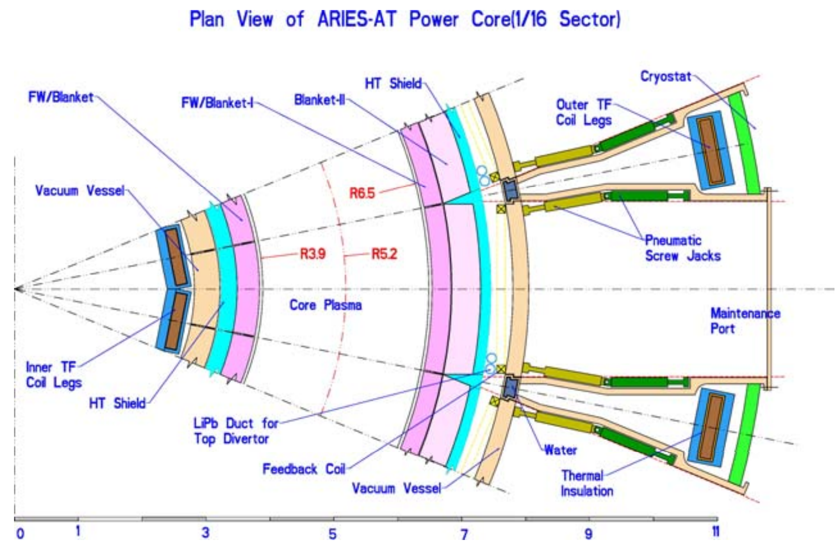
- ➢ and potential significant cost advantages Because of ease of fabrication using advanced manufacturing techniques

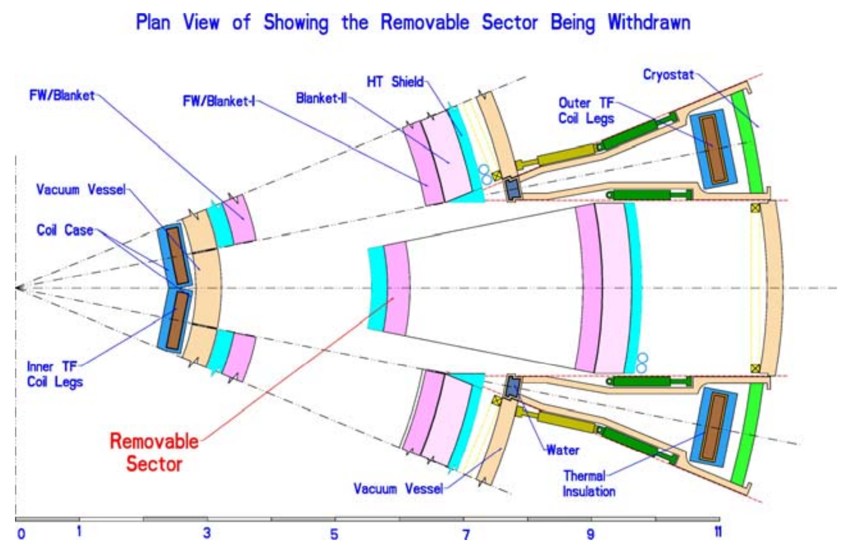




ARIES-AT Uses a Full-sector Maintenance Scheme and a High Availability Is Predicted

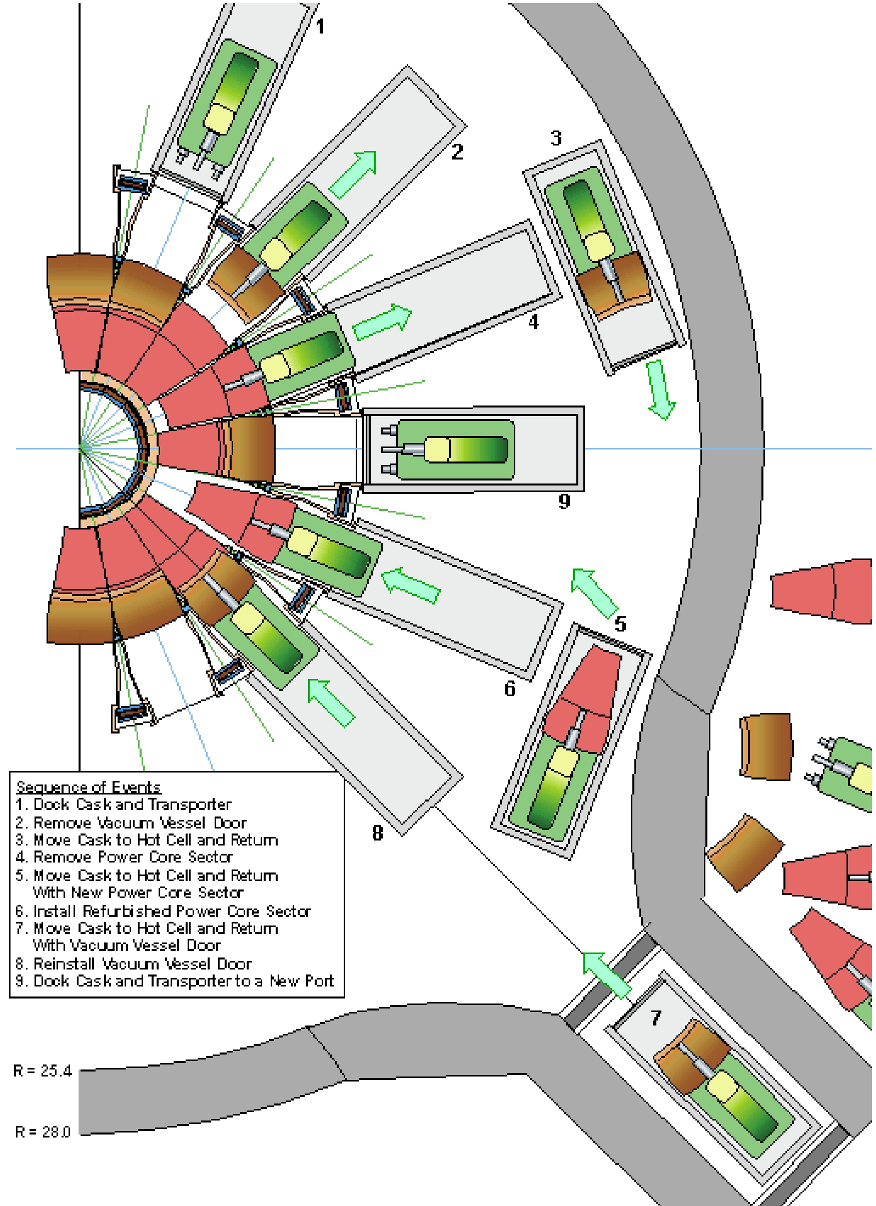




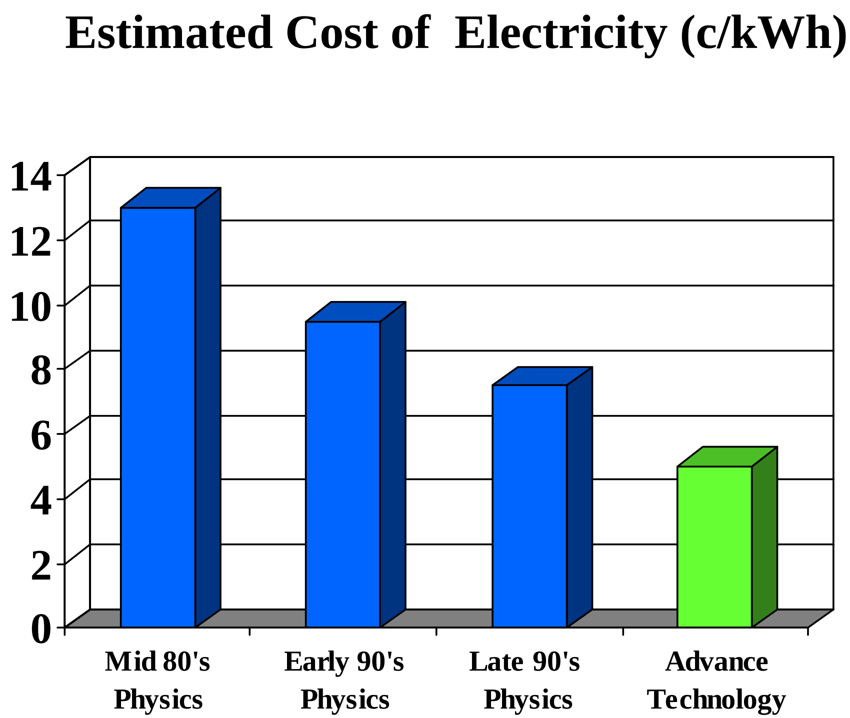


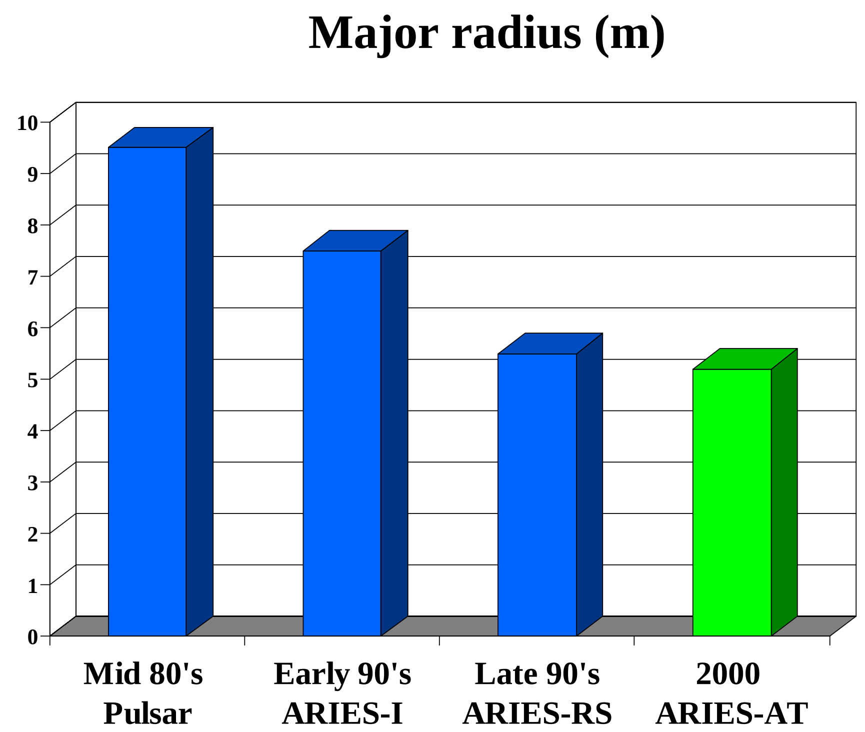
Power Core Removal Sequence

- Cask contains debris and dust
- Vacuum vessel door removed and transported to hot cell
- Core sector replaced with refurbished sector from hot cell
- Vacuum vessel door reinstalled
- Multiple casks and transporters can be used



Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology



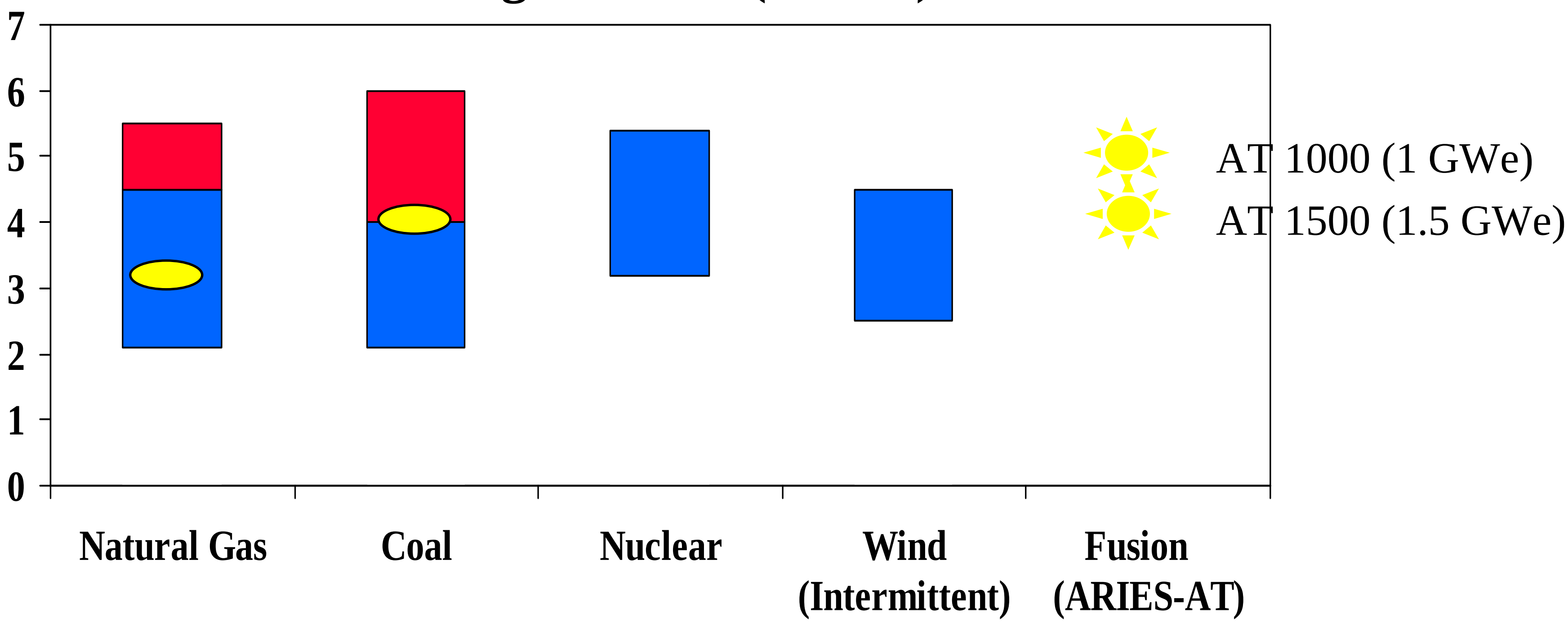


Present ARIES-AT parameters:

Major radius:	5.2 m	Fusion Power	1,720 MW
Toroidal β:	9.2%	Net Electric	1,000 MW
Wall Loading:	4.75 MW/m^2	COE	5 c/kWh

ARIES-AT is Competitive with Other Future Energy Sources

Estimated range of COE (c/kWh) for 2020*



EPRI Electric Supply Roadmap (1/99):

- Business as usual
- Impact of $100/ton Carbon Tax.

Estimates from Energy Information Agency Annual Energy Outlook 1999 (No Carbon tax).

* Data from Snowmass Energy Working Group Summary.

Main Features of ARIES-AT^2 (Advanced Technology & Advanced Tokamak)

- **High Performance Very Low-Activation Blanket:** New high-temperature SiC composite/LiPb blanket design capable of achieving ~60% thermal conversion efficiency with small nuclear-grade boundary and excellent safety & waste characterization.
- **Higher Performance Physics:** reversed-shear equilibria have been developed with up to 50% higher β than ARIES-RS and reduced current-drive power.

- **The ARIES-AT study shows that the combination of advanced tokamak modes and advanced technology leads to attractive fusion power plant with excellent safety and environmental characteristics and with a cost of electricity which is competitive with those projected for other sources of energy.**