Characteristics of Commercial Fusion Power Plants Results from ARIES-AT Study

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Electronic copy: http://aries.ucsd.edu/najmabadi/TALKS

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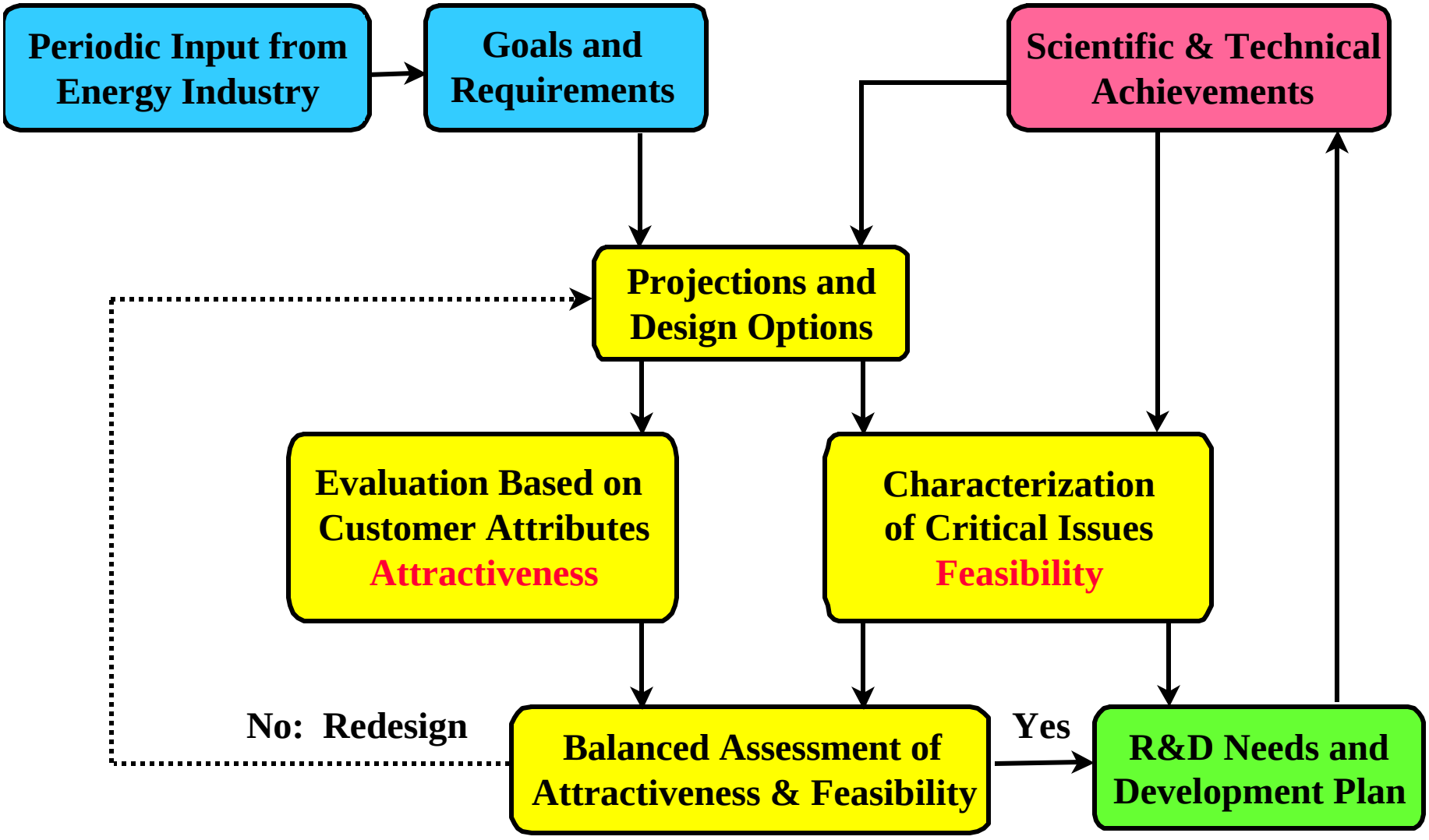
Framework:
Assessment Based on Attractiveness & Feasibility



Top-Level Requirements for Commercial Fusion Power Plants

- **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;
  - Ability to operate reliably with less than 0.1 major unscheduled shut-down per year.

- **Above requirements must be achieved consistent with a competitive life-cycle cost of electricity goal.**

GOAL: Demonstrate that Fusion Power Can Be a Safe, Clean, & Economically Attractive Option

Requirements:

- **Have an economically competitive life-cycle cost of electricity:**
  - Low recirculating power;
  - High power density;
  - High thermal conversion efficiency.
- **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.**

The ARIES-RS Study Set the Goals and Direction of Research for ARIES-AT

	ARIES-RS Performance	ARIES-AT Goals
Economics		
Power Density	Reversed-shear Plasma Radiative divertor Li-V blanket with insulating coatings	Higher performance RS Plasma, SiC composite blanket High T_c superconductors
Efficiency	610^{o}C outlet (including divertor) Low recirculating power	> 1000 ^{o}C coolant outlet > 90% bootstrap fraction
Availability	Full-sector maintenance Simple, low-pressure design	Same or better
Manufacturing		Advanced manufacturing techniques
Safety and Environmental attractiveness	Low afterheat V-alloy No Be, no water, Inert atmosphere Radial segmentation of fusion core to minimize waste quantity	SiC Composites Further attempts to minimize waste quantity

ARIES-AT^2: Physics Highlights

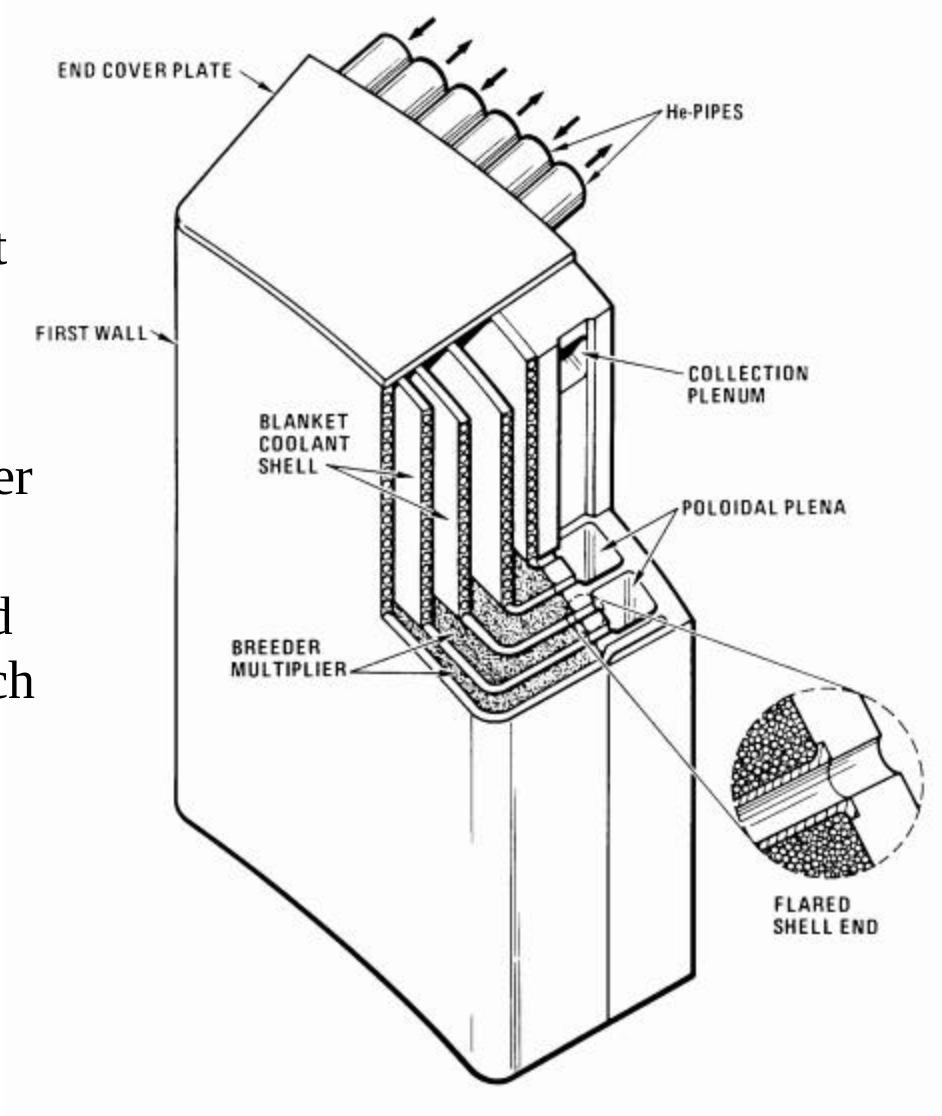
- We used the lessons learned in ARIES-ST optimization to reach a higher performance plasma;
  - Using > 99% flux surface from free-boundary plasma equilibria rather than 95% flux surface used in ARIES-RS leads to larger elongation and triangularity and higher stable β.
- ARIES-AT blanket allows vertical 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), 1cm 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^2: 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.
- 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.)

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

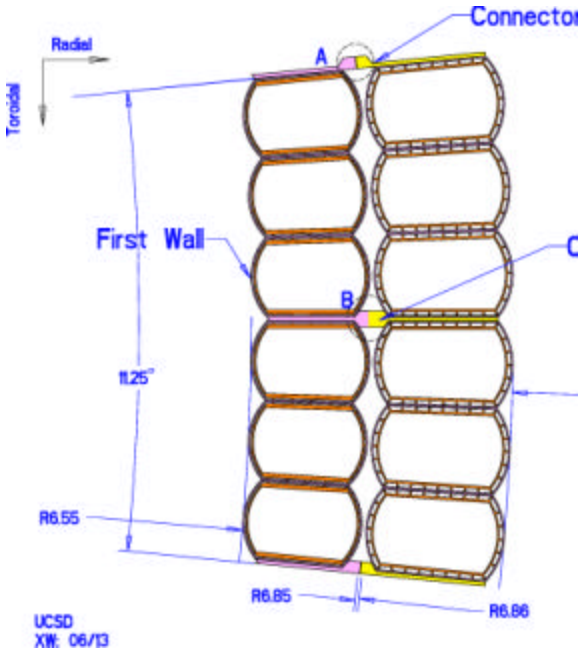
- Excellent safety & environmental characteristics (very low activation and very low afterheat).
- High performance due to high strength at high temperatures (>1000^{o}C).
- Large world-wide program in SiC:
  - New SiC composite fibers with proper stoichiometry and small O content.
  - New manufacturing 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.

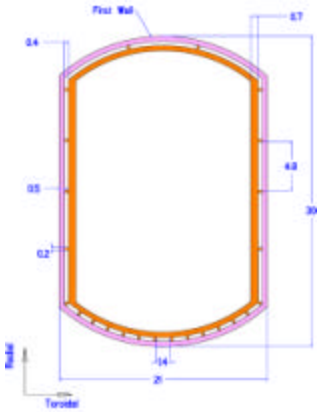


ARIES-AT^2: SiC Composite Blankets

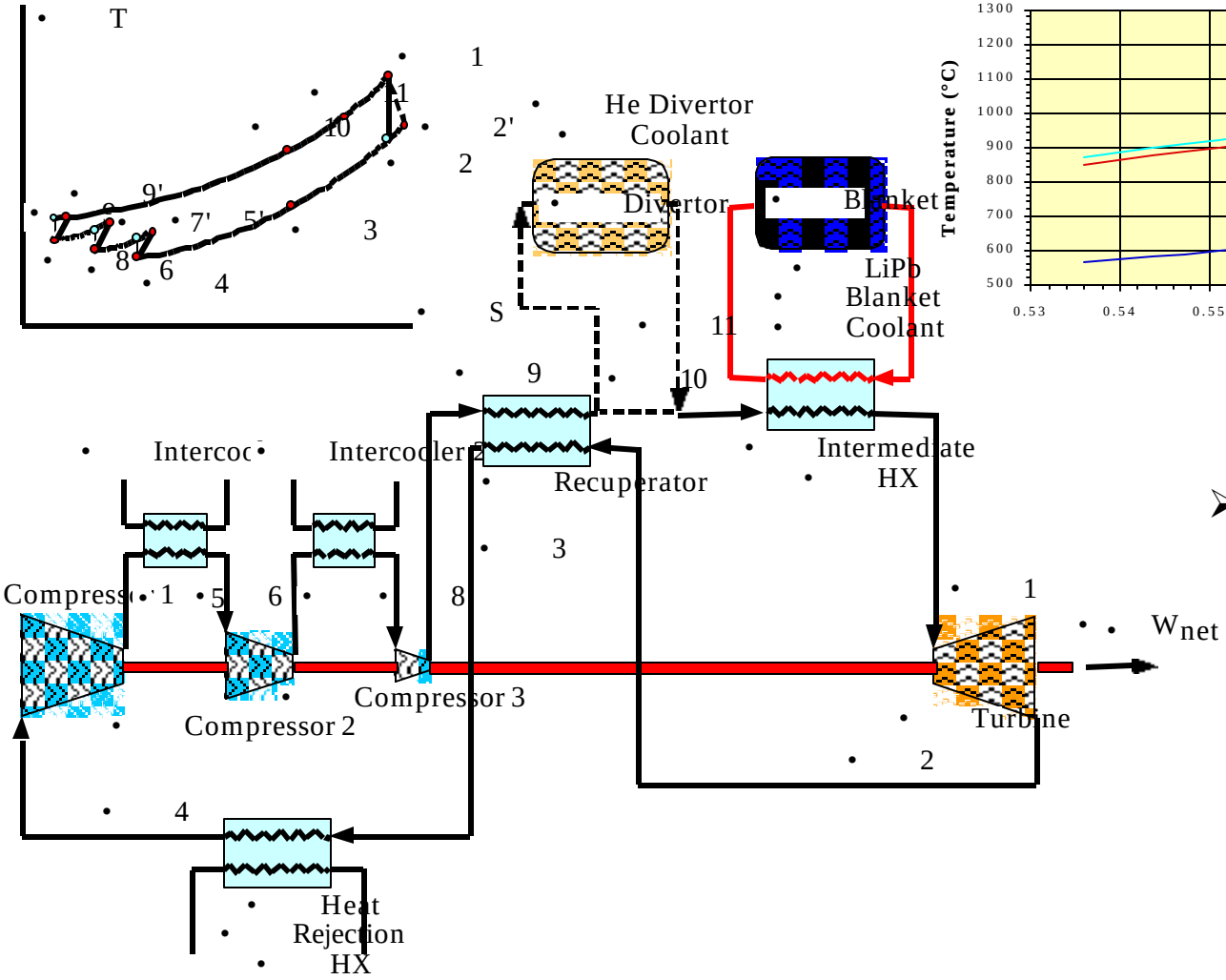
- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1100^{o}C) while keeping SiC structure temperature below 1000^{o}C leading to a high thermal efficiency of ~ 60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
- LiPb-cooled SiC composite divertor is capable of 5 MW/m^2 of heat load.

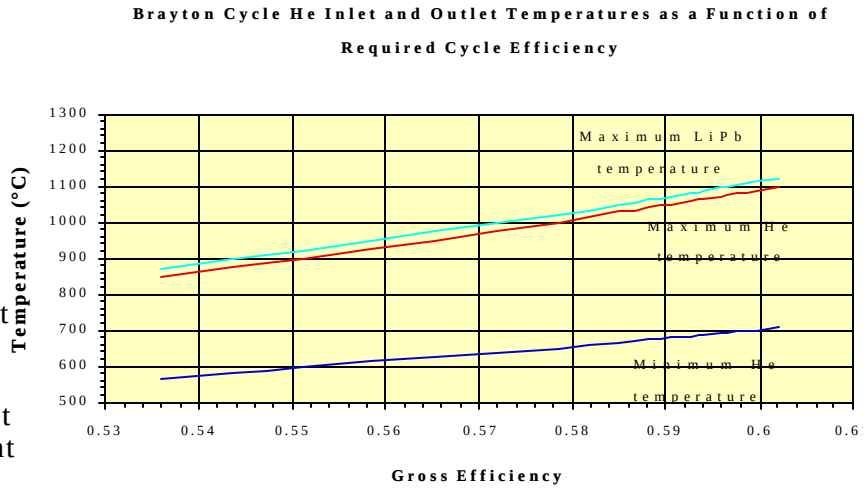
Outboard blanket & first wall





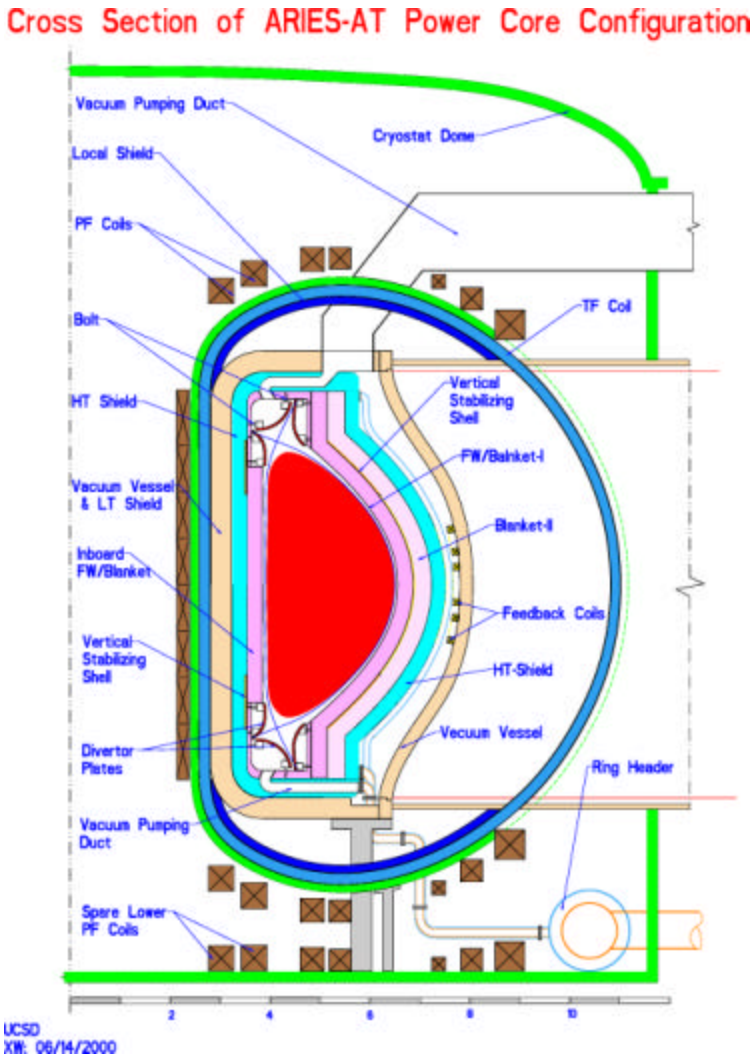
Recent Advances in Brayton Cycle Leads to Power Cycles With High Efficiency

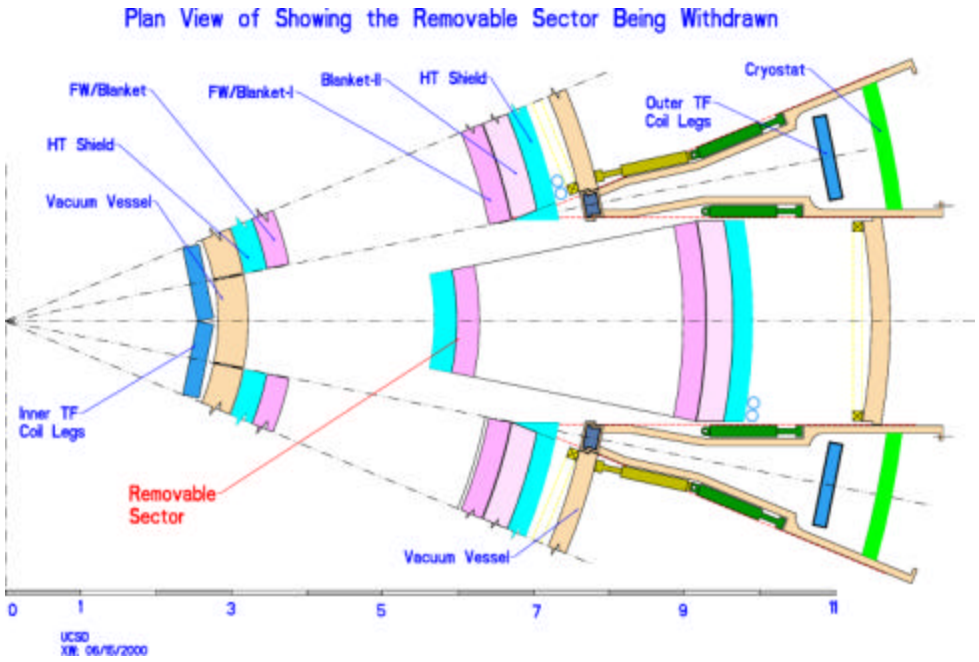




- Key improvement is the development of cheap, high-efficiency recuperators.

ARIES-AT Also Uses A Full-Sector Maintenance Scheme





Major Parameters of ARIES-RS and ARIES-AT

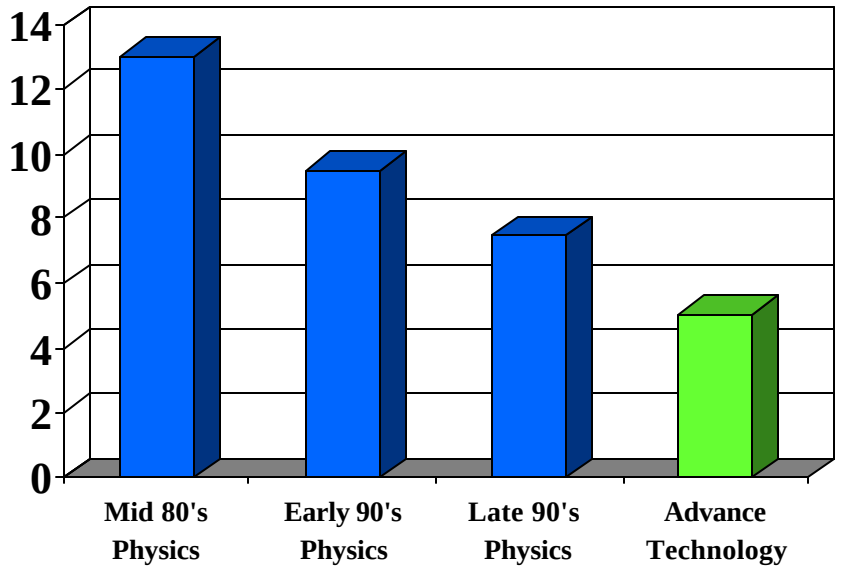
	ARIES-RS	ARIES-AT
Aspect ratio	4.0	4.0
Major toroidal radius (m)	5.5	5.2
Plasma minor radius (m)	1.4	1.3
Plasma elongation (κ_x)	1.9	2.2
Plasma triangularity (δ_x)	0.77	0.84
Toroidal β	5%	9.2%
Electron density (10^{20} m^{-3})	2.1	2.3
ITER-89P scaling multiplier	2.3	2.6
Plasma current	11	13

Major Parameters of ARIES-RS and ARIES-AT

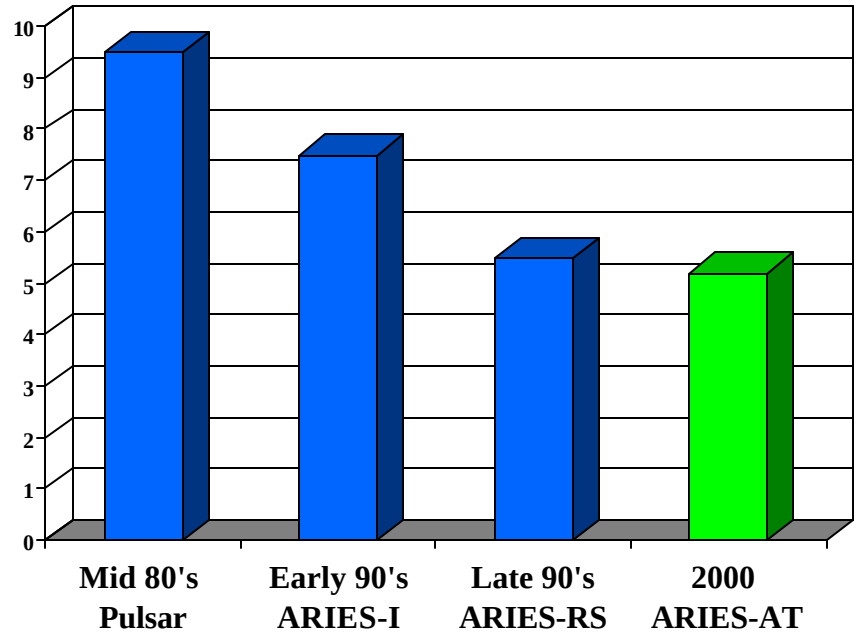
	ARIES-RS	ARIES-AT
On-axis toroidal field (T)	8	6
Peak field at TF coil (T)	16	11.4
Current-drive power to plasma (MW)	81	36
Peak/Avg. neutron wall load (MW/m^2)	5.4/ 4	4.9/3.3
Fusion power (MW)	2,170	1,755
Thermal efficiency	0.46	0.59
Gross electric power (MW)	1,200	1,136
Recirculating power fraction	0.17	0.14
Cost of electricity (mill/kWh)	76	55

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

Estimated Cost of Electricity (c/kWh)



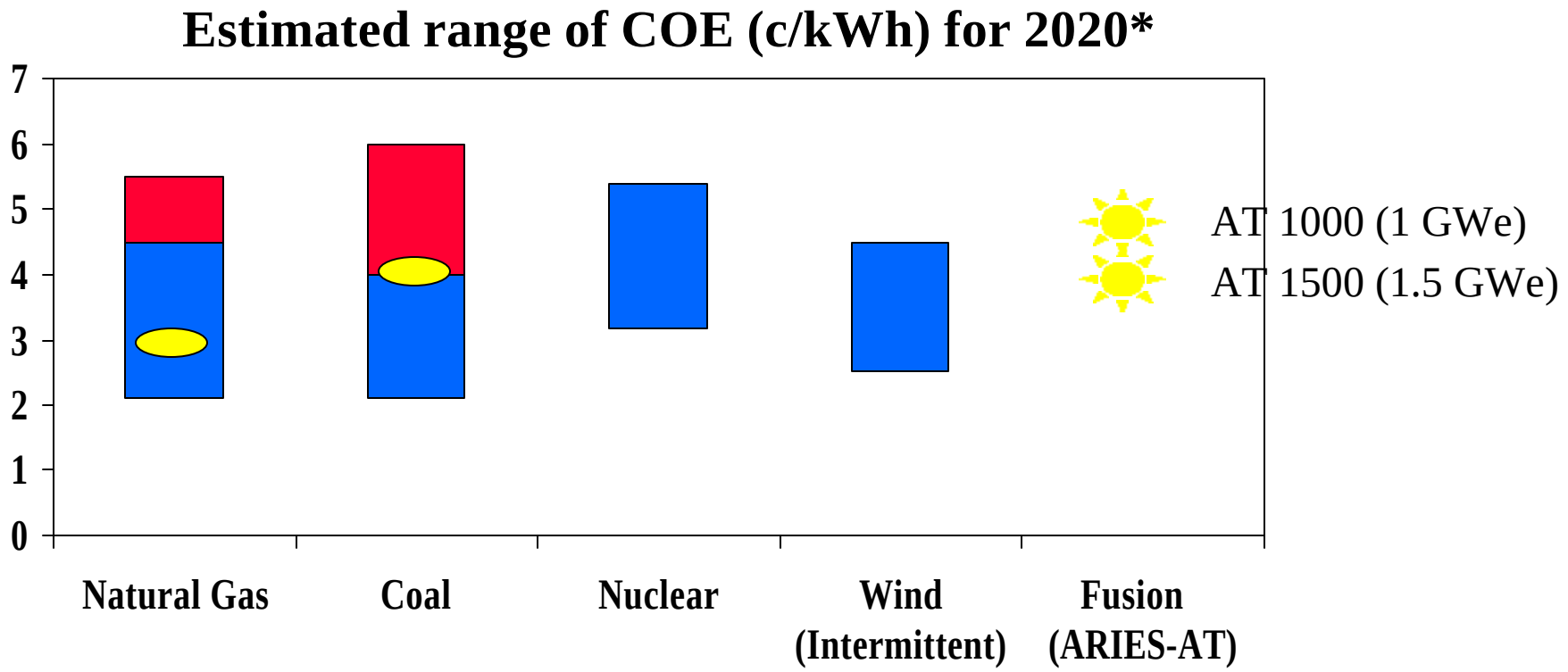
Major radius (m)



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	5.5 c/kWh

ARIES-AT is Competitive with Other Future Energy Sources



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.**