Prospect for Attractive Fusion Power (Focus on tokamaks)

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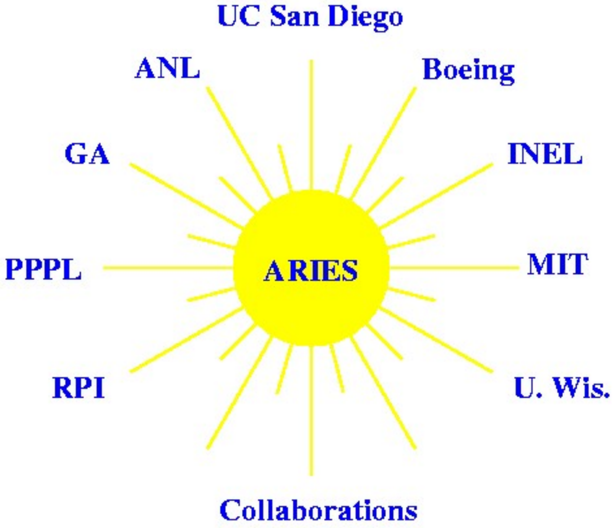


1) **Do we have an attractive vision for the final product?**

Elements of the Case for Fusion Power Were Developed through Interaction with Representatives of U.S. Electric Utilities and Energy Industry

- **Have an economically competitive life-cycle cost of electricity**
- **Gain Public acceptance by having excellent safety and environmental characteristics**
  - ✓ No disturbance of public's day-to-day activities
  - ✓ No local or global atmospheric impact
  - ✓ No need for evacuation plan
  - ✓ No high-level waste
  - ✓ Ease of licensing

Low-activation material

- **Reliable, available, and stable as an electrical power source**
  - ✓ Have operational reliability and high availability
  - ✓ Closed, on-site fuel cycle
  - ✓ High fuel availability
  - ✓ Capable of partial load operation
  - ✓ Available in a range of unit sizes

Fusion physics & technology

A dramatic change occurred in 1990: Introduction of Advanced Tokamak

- Our vision of a fusion system in 1980s was a large pulsed device.
  - ✓ Non-inductive current drive is inefficient.
- Some important achievements in 1980s:
  - ✓ Experimental demonstration of bootstrap current;
  - ✓ Development of ideal MHD codes that agreed with experimental results.
- Development of steady-state power plant concepts (ARIES-I and SSTR) based on the trade-off of bootstrap current fraction and plasma β (1990)

  ARIES-I: β_N= 2.9, β=2%, P_{cd}=230 MW

Last decade: Reverse Shear Regime

- Excellent match between bootstrap & equilibrium current profile at high β.
- Requires wall stabilization (Resistive-wall modes).
- Internal transport barrier.

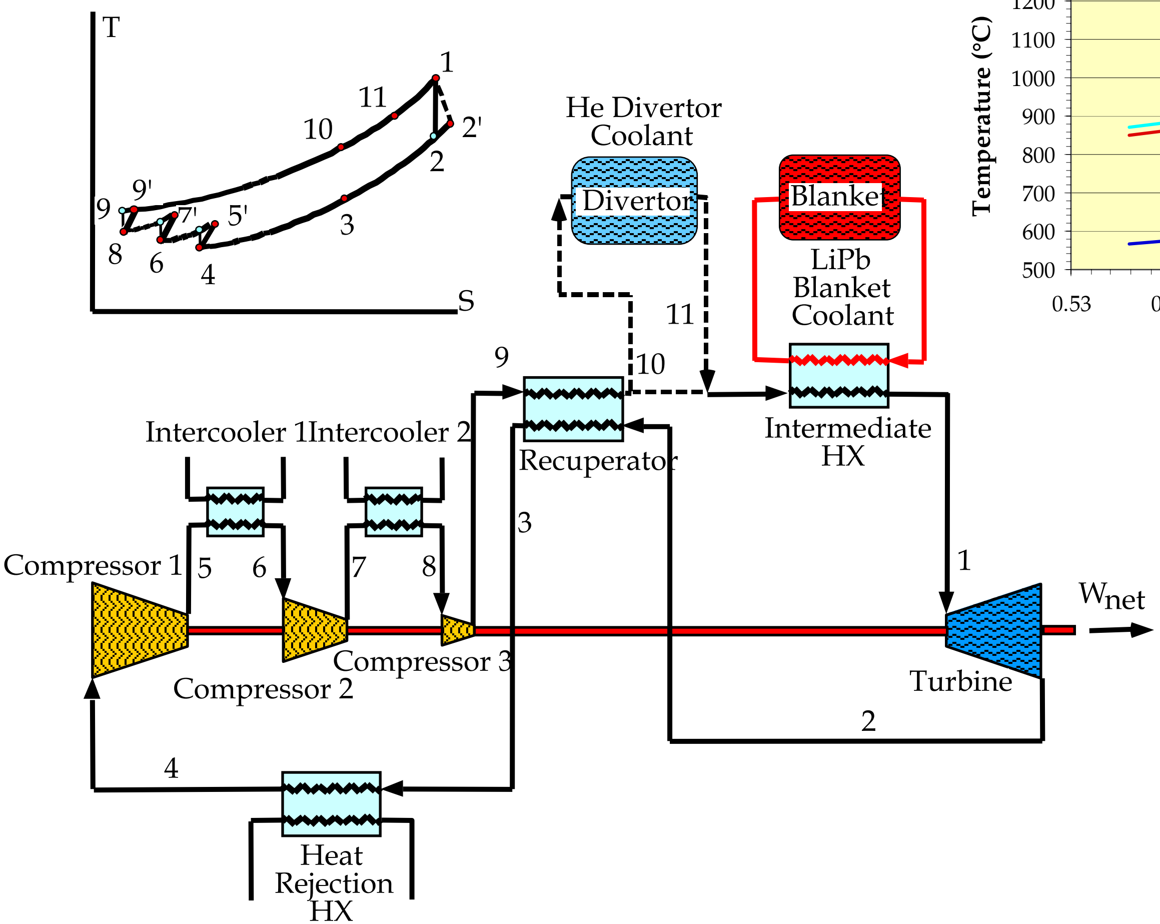
Advanced Tokamak lead to attractive power plants

	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/m²)	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

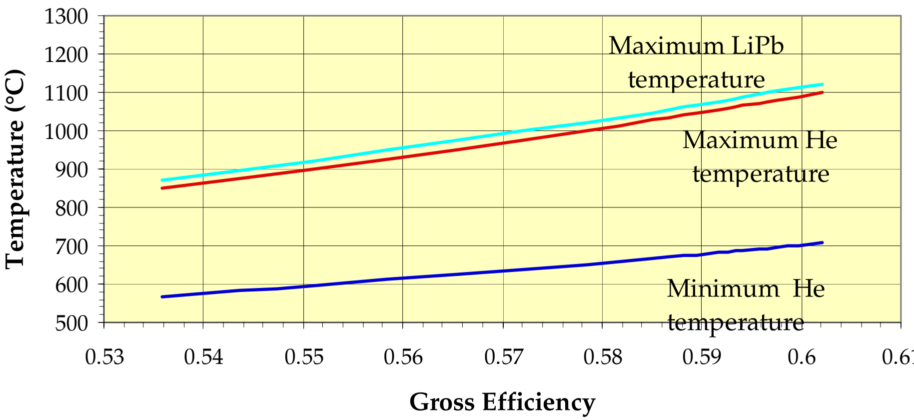
Approaching COE insensitive of power density

Reduced COE mainly due to advanced technology

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



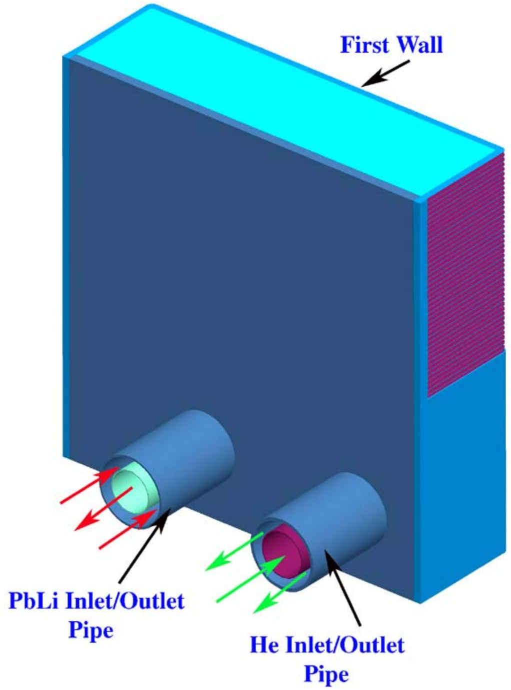
Brayton Cycle He Inlet and Outlet Temperatures as a Function of Required Cycle Efficiency

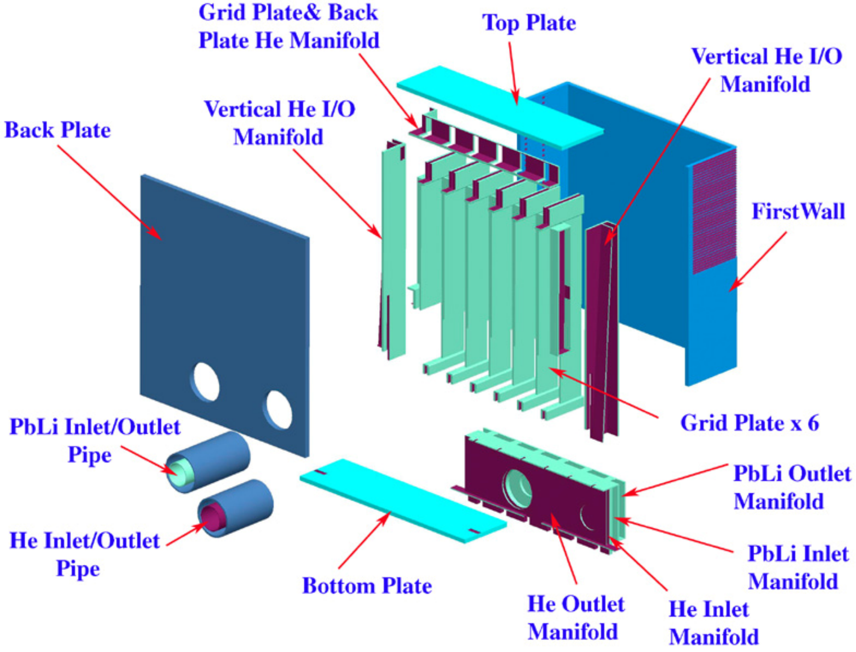


- Key improvement is the development of cheap, high-efficiency recuperators.

ARIES-ST Featured a High-Performance Ferritic Steel Blanket

- Originally developed for ARIES-ST, further developed by EU (FZK).
- Typically, the coolant outlet temperature is limited to the max. operating temperature of structural material (550^{o}C for ferritic steels).
- A coolant outlet temperature of 700^{o}C is achieved by using a coolant/breeder (LiPb), cooling the structure by He gas, and SiC insulator lining PbLi channel for thermal and electrical insulation.

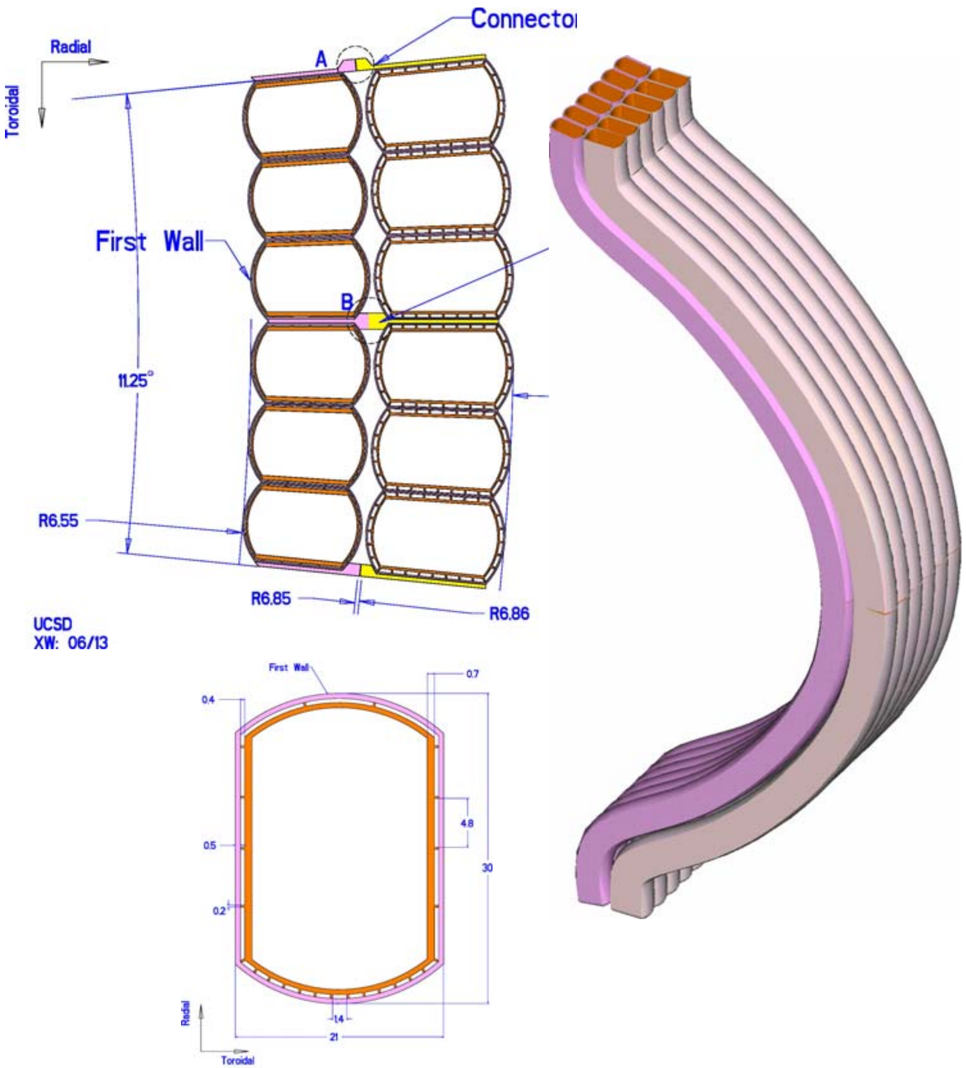




ARIES-AT^2: SiC Composite Blankets

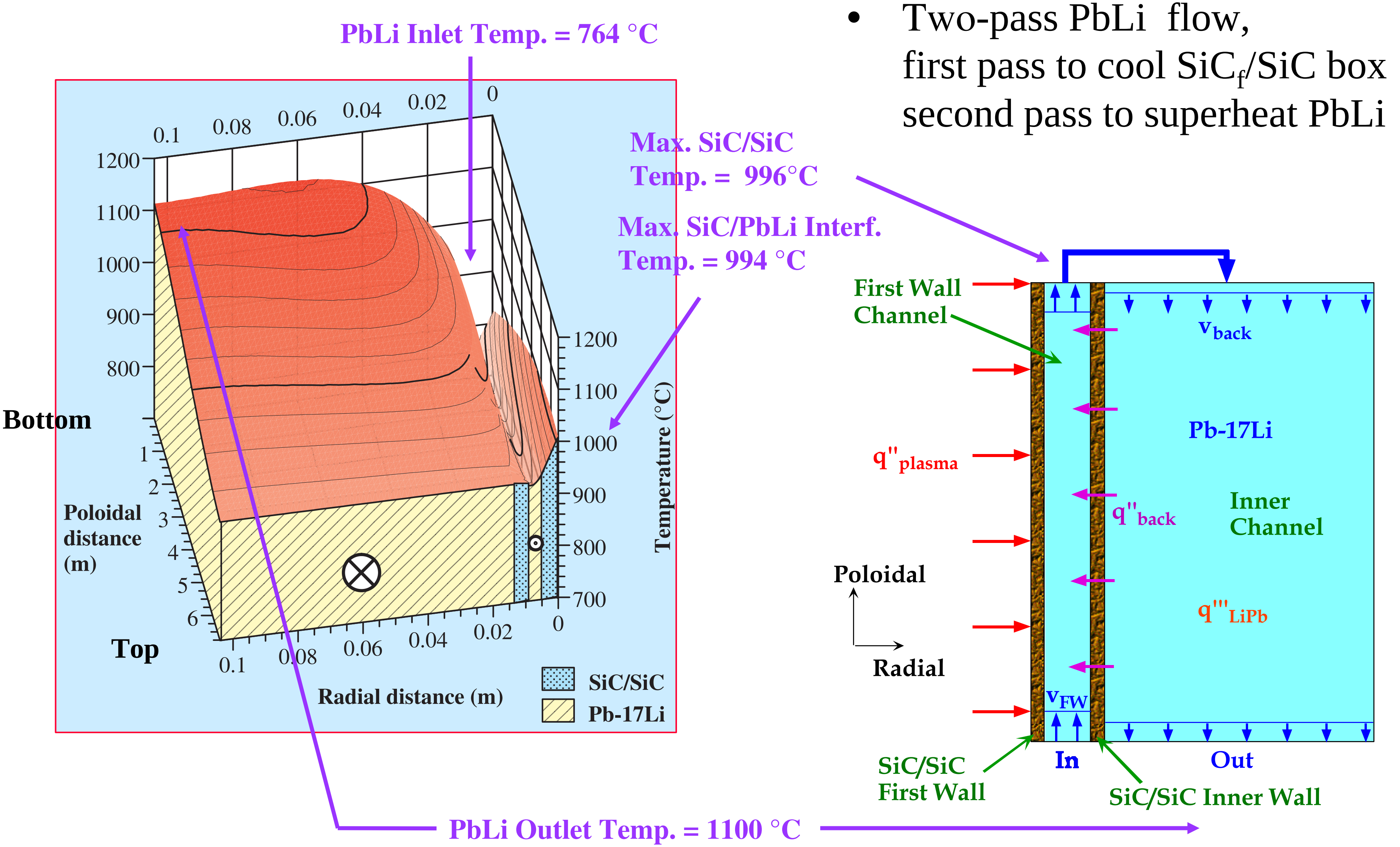
- **Simple, low pressure design with SiC structure and LiPb coolant and breeder.**
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
- LiPb-cooled SiC composite divertor is capable of 5 MW/m^2 of heat load.
- Innovative design leads to high LiPb outlet temperature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

Outboard blanket & first wall



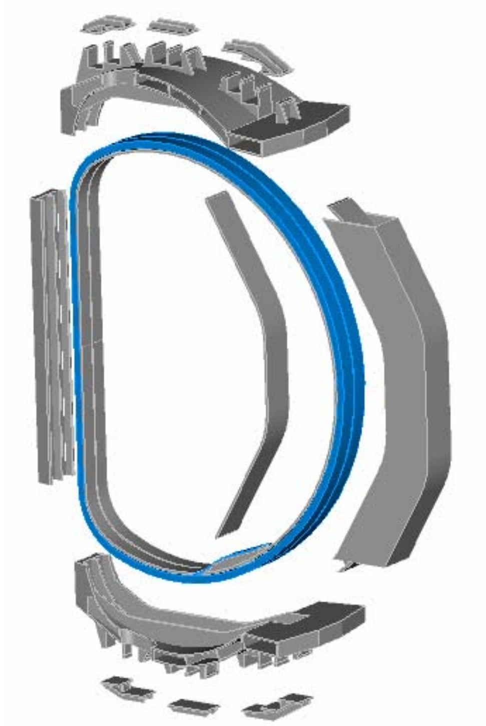
Innovative Design Results in a LiPb Outlet Temperature of 1,100ºC While Keeping SiC Temperature Below 1,000ºC

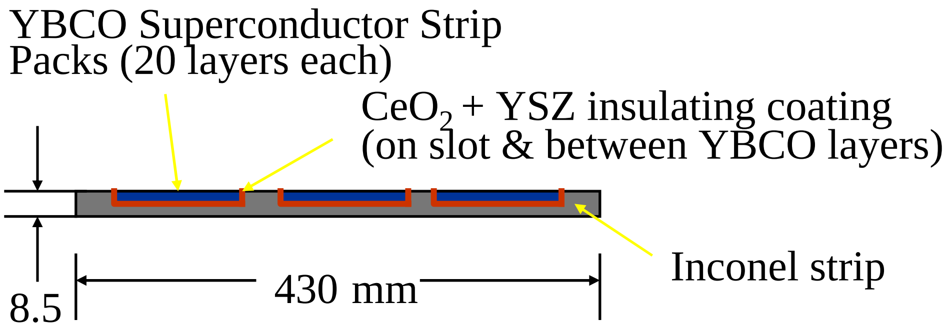
- Two-pass PbLi flow,
  first pass to cool SiC_f/SiC box
  second pass to superheat PbLi



Use of High-Temperature Superconductors Simplifies the Magnet Systems

- HTS does offer <u>operational</u> 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



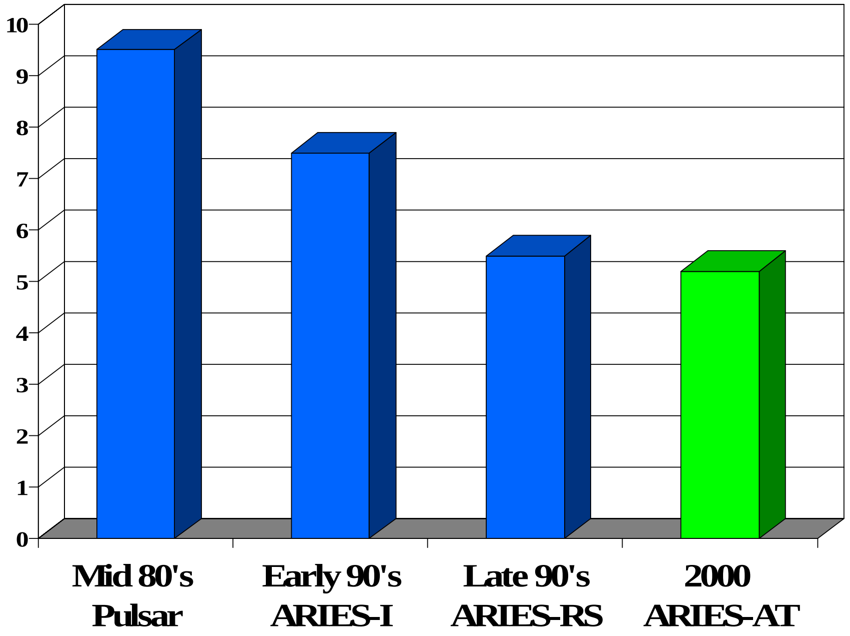


- **Epitaxial YBCO**

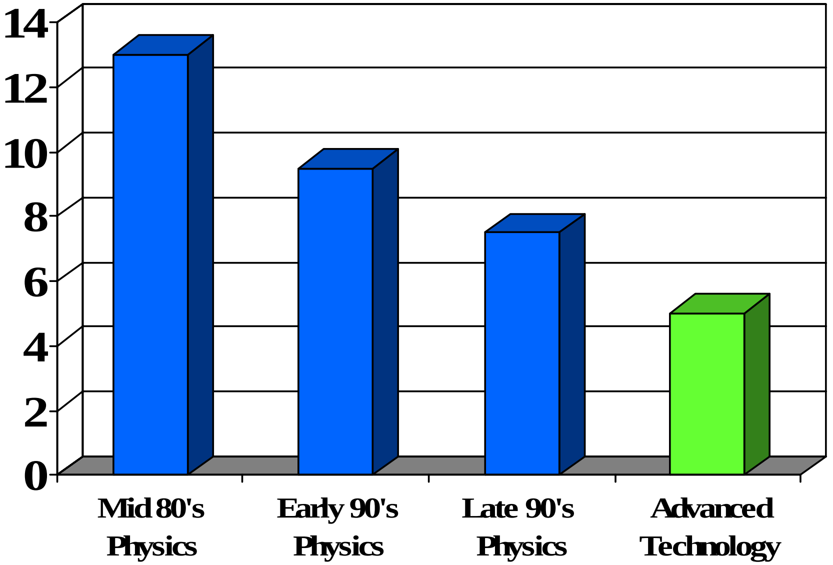
  Inexpensive manufacturing would consist of layering HTS on structural shells with minimal winding!

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

Major radius (m)



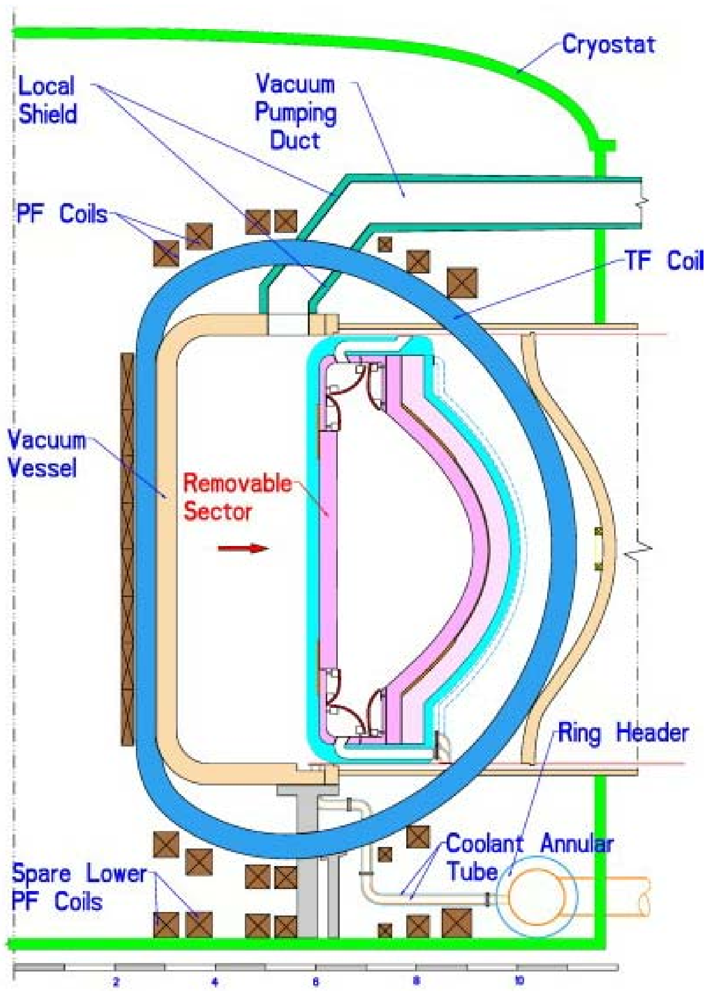
Estimated Cost of Electricity (c/kWh)



Approaching COE insensitive of power density

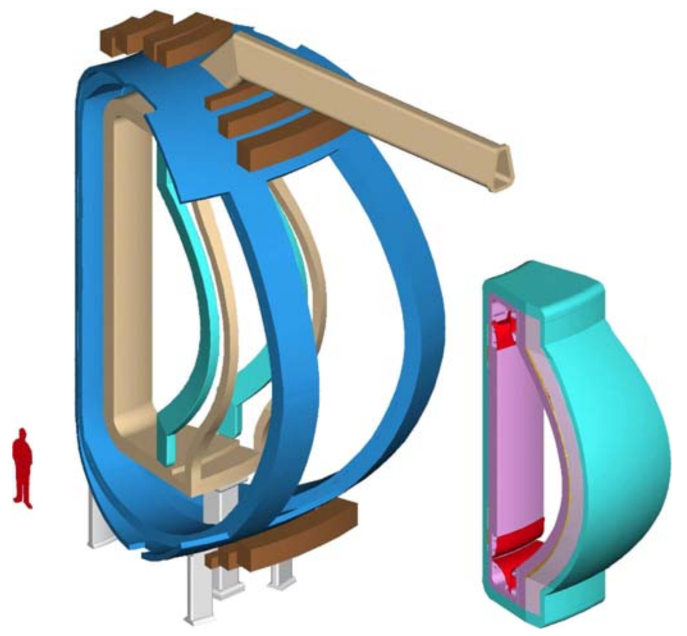
Advanced Technologies is the main lever in reducing fusion power plant costs

Modular sector maintenance enables high availability

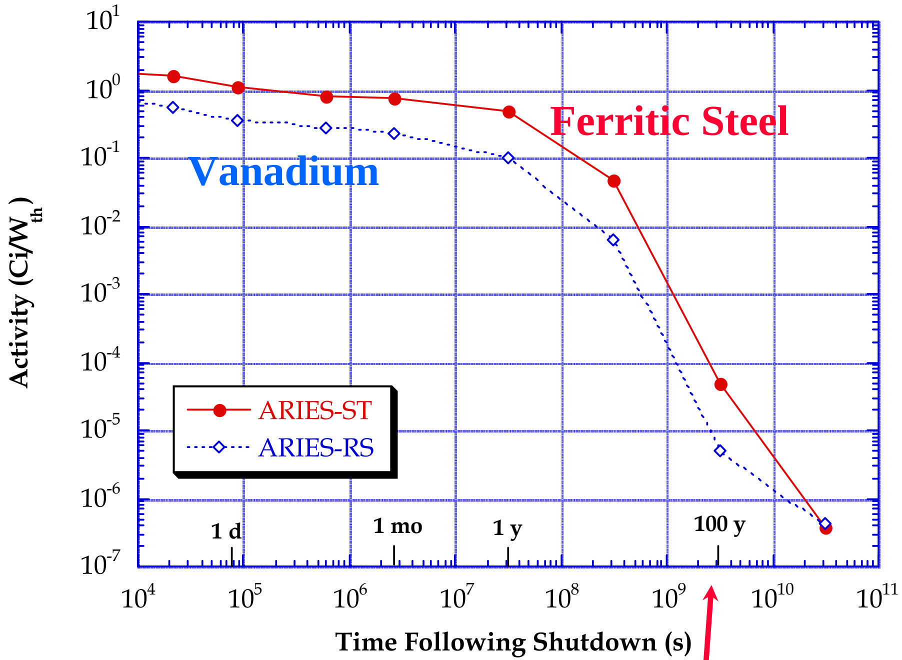


ARIES-AT elevation view

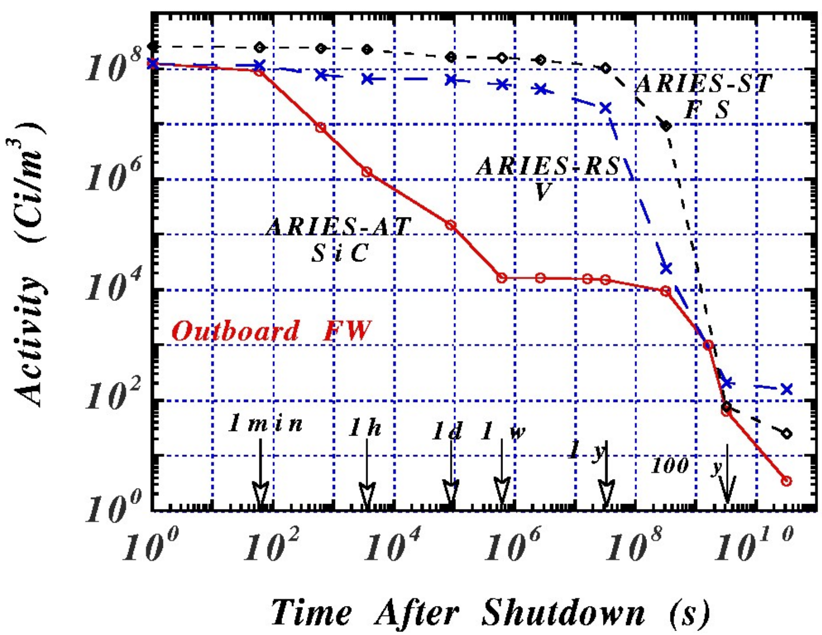
- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks



Radioactivity Levels in Fusion Power Plants Are Very Low and Decay Rapidly after Shutdown

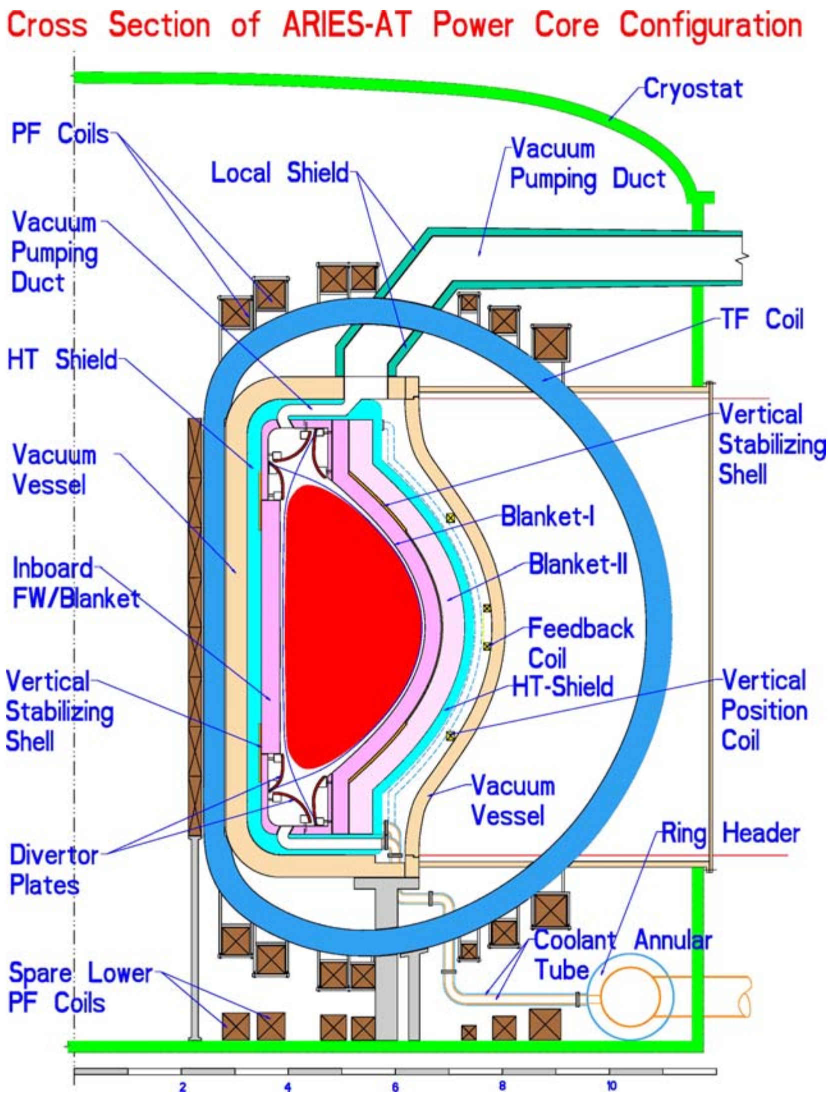


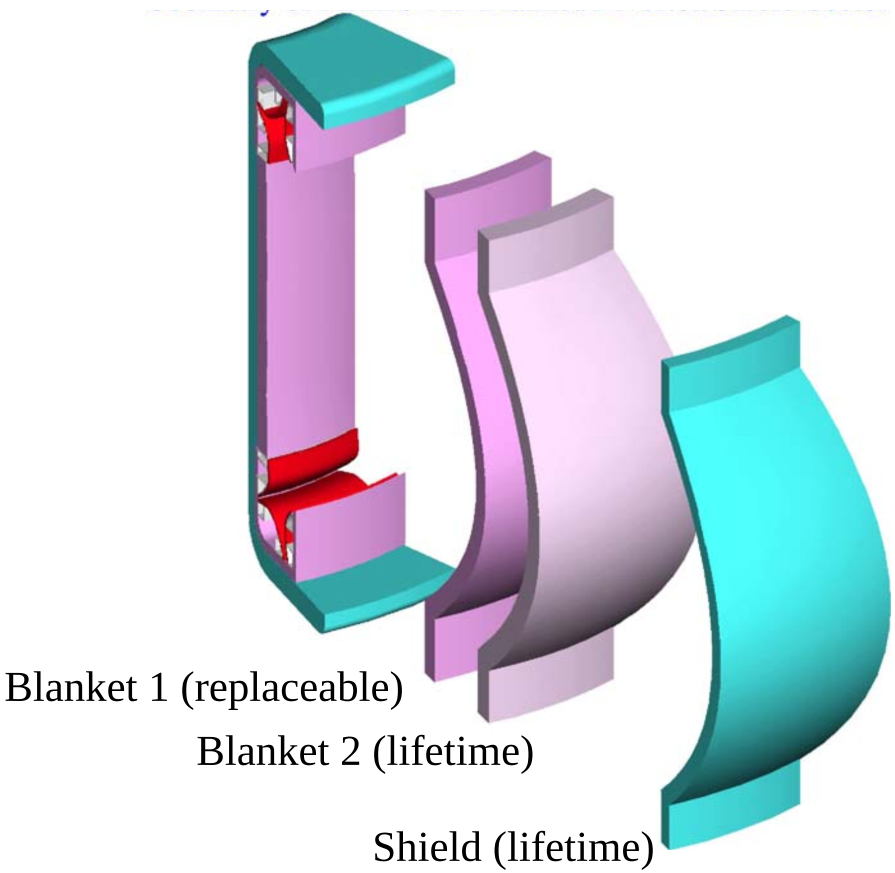
- SiC composites lead to a very low activation and afterheat.
- All components of ARIES-AT qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.



After 100 years, only 10,000 Curies of radioactivity remain in the 585 tonne ARIES-RS fusion core.

Fusion Core Is Segmented to Minimize the Rad-Waste

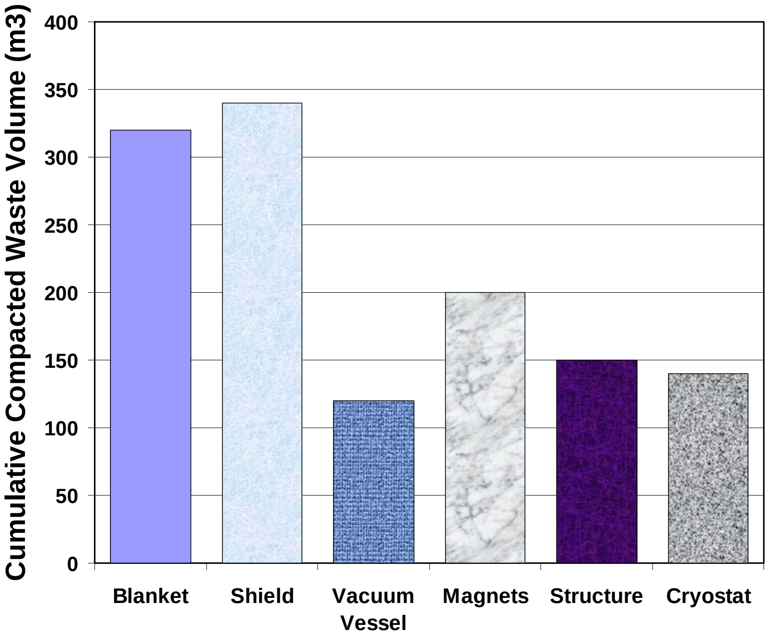


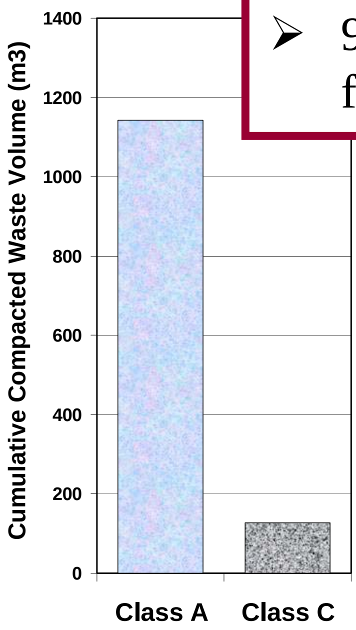


- Only "blanket-1" and divertors are replaced every 5 years

Generated radioactivity waste is reasonable

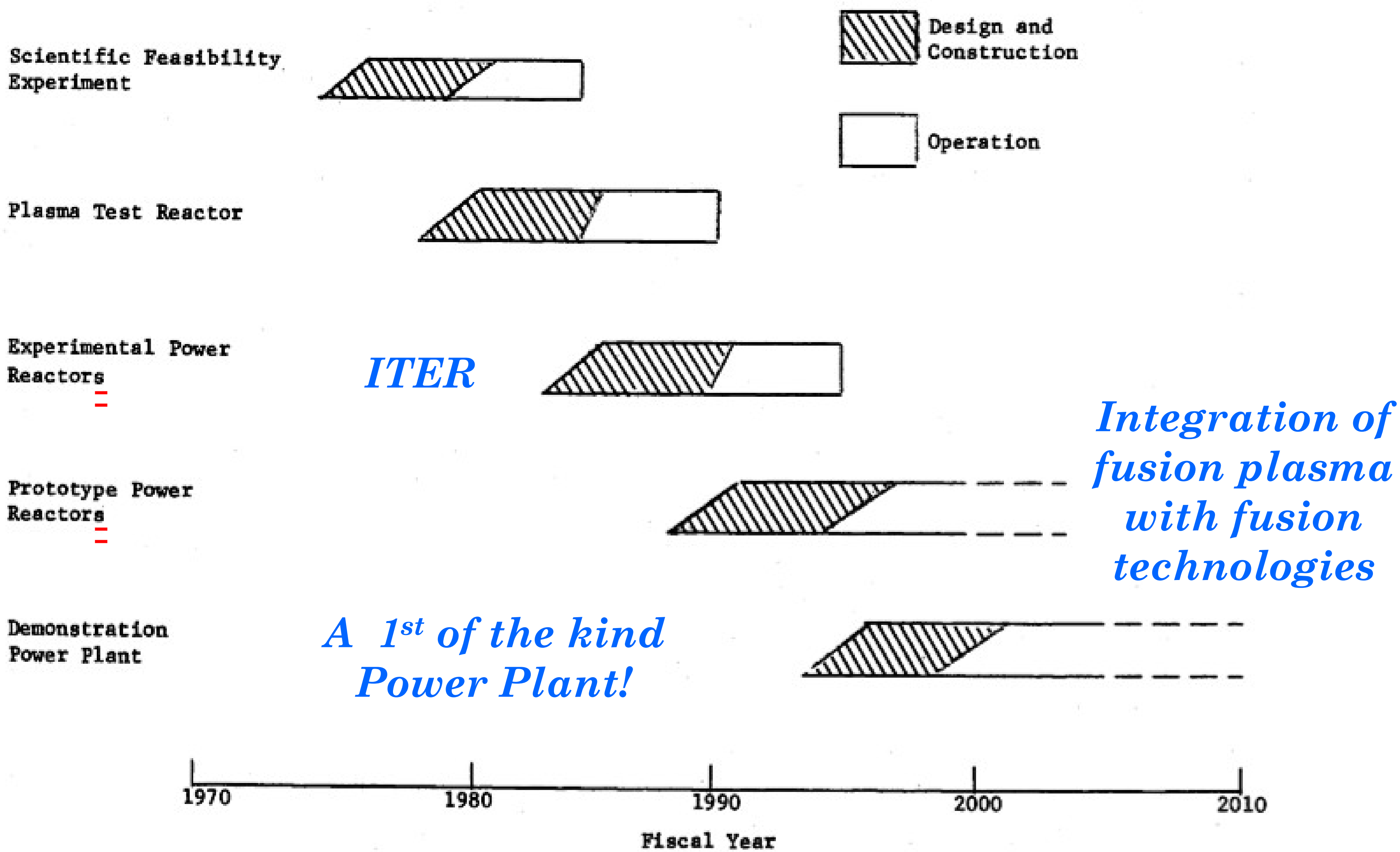
- 1270 m³ of Waste is generated after 40 full-power year (FPY) of operation (~50 years)
  - ✓ Coolant is reused in other power plants
  - ✓ 29 m³ every 4 years (component replacement)
  - ✓ 993 m³ at end of service
- Equivalent to ~ 30 m³ of waste per FPY
  - ✓ Effective annual waste can be reduced by increasing plant service life.





- 90% of waste qualifies for Class A disposal

2) How to we get from ITER to an attractive final product



Projected Fusion-Reactor Development Program
Wash-1267, July 1973

"Fusion Power: Research and Development Requirements." Division of Controlled Thermonuclear Research (AEC).

In the ITER area,
we need to develop
a 5,000 ft view

A holistic optimization approach should drive the development path.

Traditional Approach: Ask each scientific area (i.e., plasma, blanket, …)

- What are the remaining major R&D areas?
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (e.g., fission reactors)? What other major facilities are needed?

Holistic Approach: Fusion energy development should be guided by the requirements for an attractive fusion energy source

- What are the remaining major R&D areas?
  - ✓ What it the impact of this R&D on the attractiveness of the final product.
- Which of the remaining major R&D areas can be explored in existing devices or simulation facilities (i.e., fission reactors)? What other major facilities are needed?
  - ✓ Should we attempt to replicate power plant conditions in a scaled device or Optimize facility performance relative to scaled objectives

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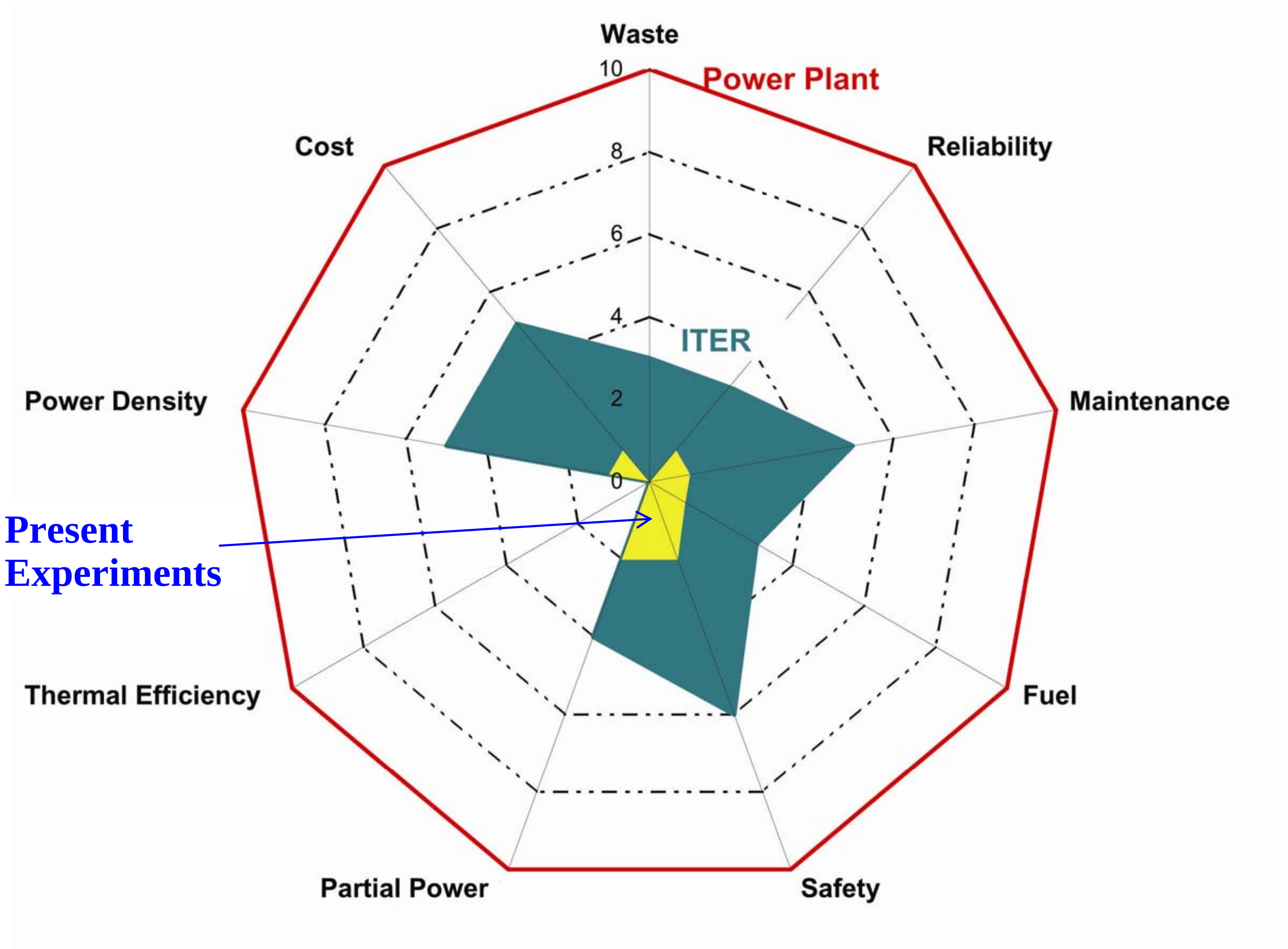
Fusion physics & technology

Existing facilities fail to address essential features of a fusion energy source

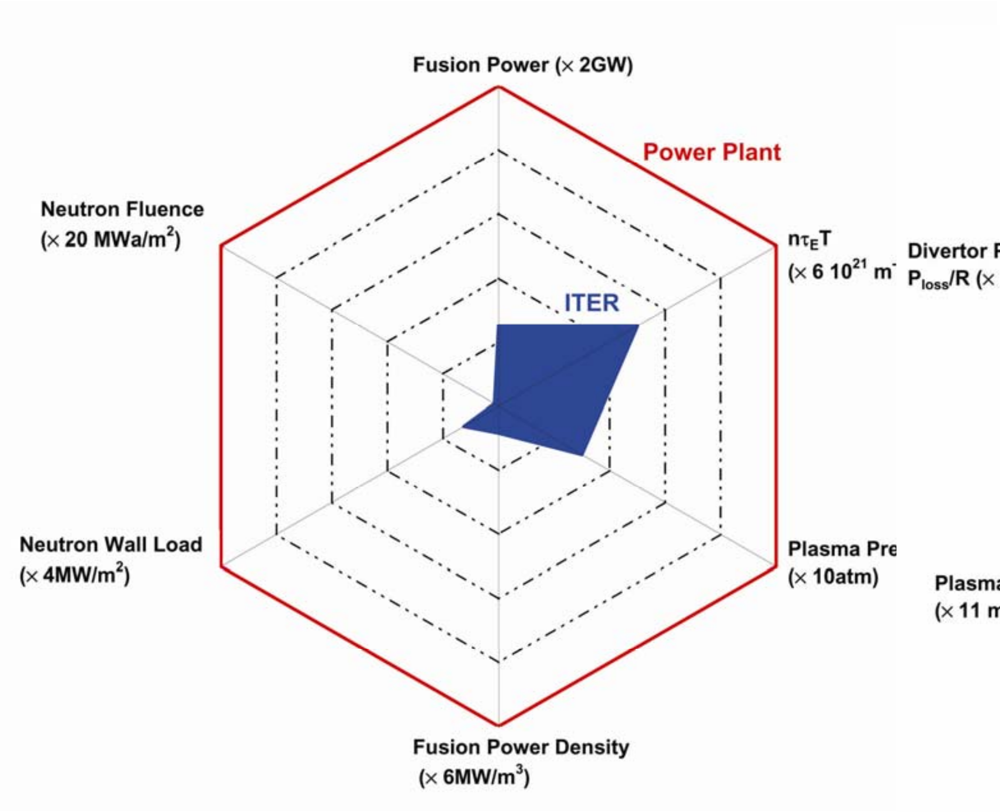
Metric	ITER	
waste	3	need to deal with it, but wrong materials, little fluence
reliability	3	some machine operation, little fluence
maintenance	5	unprototypic construction, modules replaced
fuel	3	tritium handling, but no breeding, no fuel cycle
safety	6	hazards are lower, operations different
partial power	4	experience with operating modes
thermal efficiency	0	no power production, low temperature, wrong materials
power density	5	low average power density, local regions of HHF
cost	5	1st of a kind reactor costs, cost reduction needed

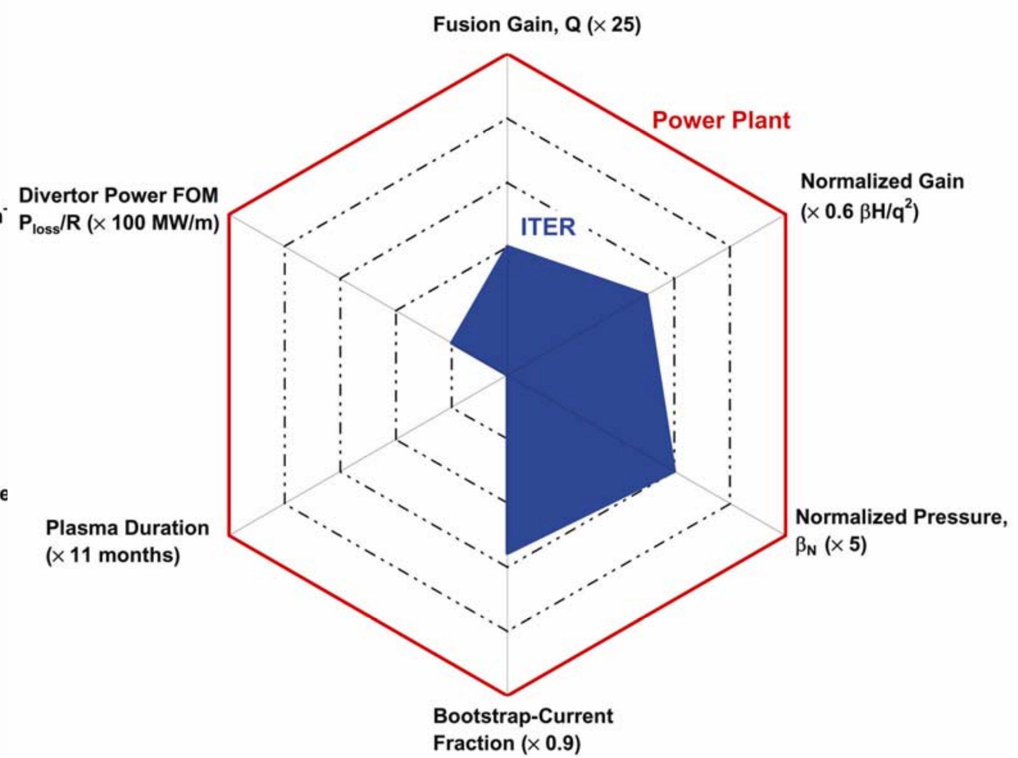
Metric	D3 / JET	
waste	0	little relevance
reliability	1	some machine operation, no fluence
maintenance	1	experience moving tokamak equipment
fuel	1	Some tritium handling, no breeding, no fuel cycle
safety	2	hazards much lower, operations much different
partial power	2	experience with operating modes
thermal efficiency	0	no power conversion
power density	1	low power handling required, some divertor heating
cost	1	not relevant to a power plant

ITER is a major step forward but there is a long road ahead.



Power plant features and not individual parameters should drive the development path





- Absolute parameters

- Dimensionless parameters

There is a need to examine fusion development scenarios in detail

- We need to start planning for facilities and R&D needed between ITER and a power plant.
- Metrics will be needed for cost/benefit/risk tradeoffs
- An integrated, "holistic" approach, <u>based on the requirements for an attractive fusion energy source</u>, provides a path to an optimized development scenario and R&D prioritization.
- **Developing power-plant fusion technologies is the pace-setting element in developing fusion.**
- Fusion and advanced fission systems have similar R&D issues, we can leverage substantially on advanced fission effort (but we need to be at the table).