Perspectives on Fusion Electric Power Plants

Farrokh Najmabadi
University of California, San Diego,
La Jolla, CA

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Electronic copy: http://aries.uscd/edu/najmabadi/
ARIES Web Site: http://aries.ucsd.edu/ARIES/

Evolution of the Vision of Fusion Power Plants
(last 15 years)
1. Plasma Physics

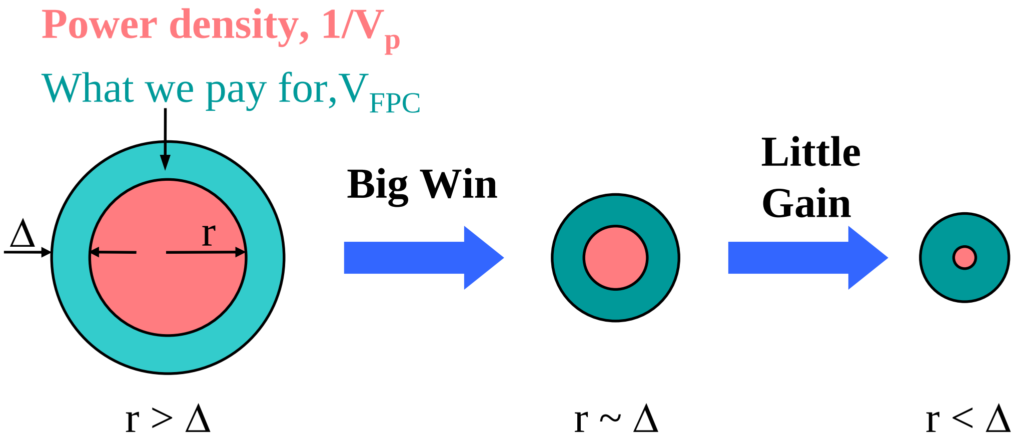
A dramatic change occurred in 1990: Introduction of Advanced Tokamak

- 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 stead-state power plant concepts (ARIES-I and SSTR) based on the trade-off of bootstrap current fraction and plasma β

- ARIES-I was still too large and too expensive: Utilize advance technologies:
  - ✓ Utilized high field magnets to improve the power density
  - ✓ Introduced SiC composite to achieve excellent safety & environmental characteristics.

Directions for Improvement

Increase Power Density



- ✓ Improvement “saturates” at ~5 MW/m^2 peak wall loading (for a 1GWe plant).
- ✓ A steady-state, first stability device with Nb_3Sn technology has a power density about 1/3 of this goal.

High-Field Magnets

- ✓ ARIES-I with 19 T at the coil (cryogenic).
- ✓ Advanced SSTR-2 with 21 T at the coil (HTS).

High bootstrap, High β

- ✓ 2nd Stability: ARIES-II/IV
- ✓ Reverse-shear: ARIES-RS, ARIES-AT, A-SSRT2

Decrease Recirculating Power Fraction

- ✓ Improvement “saturates” about Q ~ 40.
- ✓ A steady-state, first stability device with Nb_3Sn Tech. has a recirculating fraction about 1/2 of this goal.

Reverse Shear Plasmas Lead to Attractive Tokamak Power Plants

First Stability Regime

- Does Not need wall stabilization (Resistive-wall modes)
- Limited bootstrap current fraction (< 65%), limited β_N= 3.2 and β=2%,
- **ARIES-I:** Optimizes at high A and low I and high magnetic field.

Reverse Shear Regime

- Requires wall stabilization (Resistive-wall modes)
- Excellent match between bootstrap & equilibrium current profile at high β.
- Internal transport barrier
- **ARIES-RS** (medium extrapolation): β_N= 4.8, β=5%, P_{cd}=81 MW (achieves ~5 MW/m^2 peak wall loading.)
- **ARIES-AT** (aggressive extrapolation): β_N= 5.4, β=9%, P_{cd}=36 MW (high β is used to reduce peak field at magnet)

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 designs Correspond to Experimental Progress in a Burning Plasma Experiment

Pulsar (pulsed-tokamak):
- Trade-off of β with bootstrap
- Expensive PF system, under-performing TF

“Conventional” Pulsed plasma: Explore burn physics

ARIES-I (first-stability steady-state):
- Trade-off of β with bootstrap
- High-field magnets to compensate for low β

Demonstrate steady-state first-stability operation.

ARIES-RS (reverse shear):
- Improvement in β and current-drive power
- Approaching COE insensitive of current drive

Explore reversed-shear plasma

a) Higher Q plasmas

b) At steady state

ARIES-AT (aggressive reverse shear):
- Approaching COE insensitive of power density
- High β is used to reduce toroidal field

Explore envelopes of steady-state reversed-shear operation

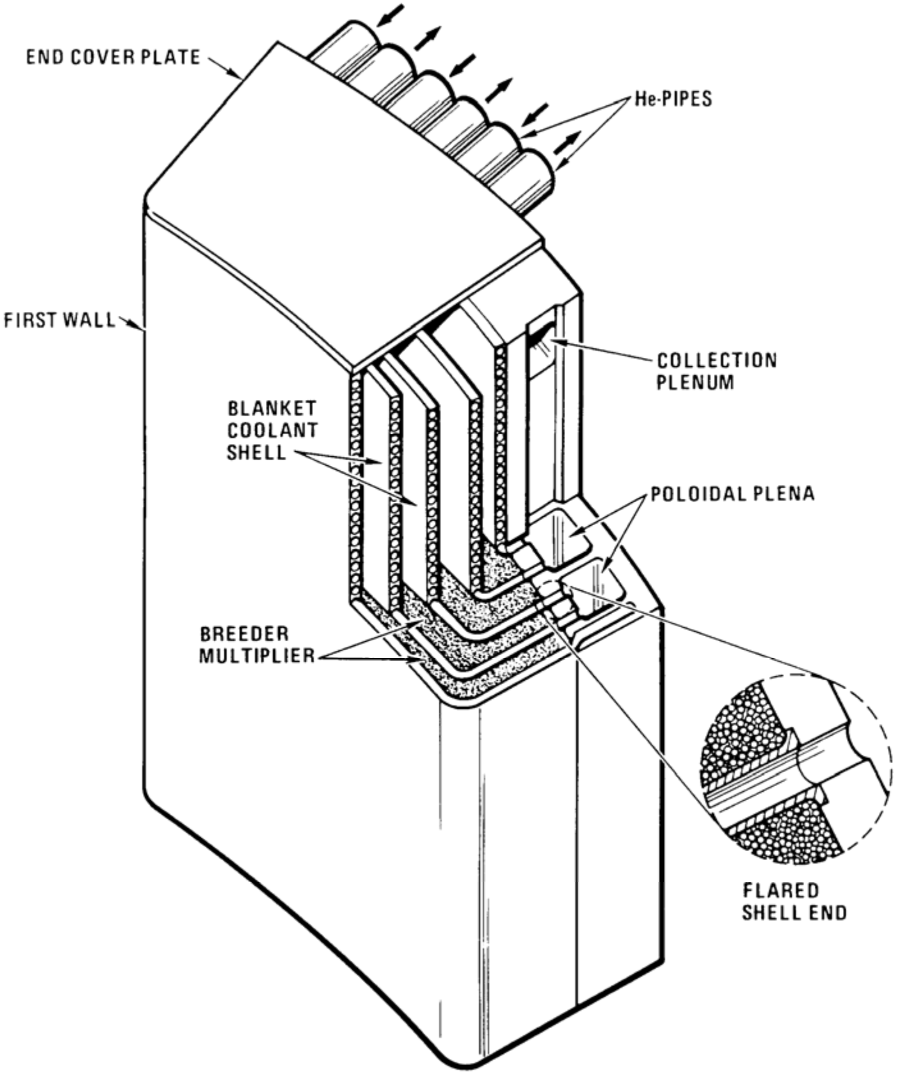
Improved Physics

Evolution of the Vision of Fusion Power Plants

2. Fusion “Technologies”

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 or CVI result 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

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

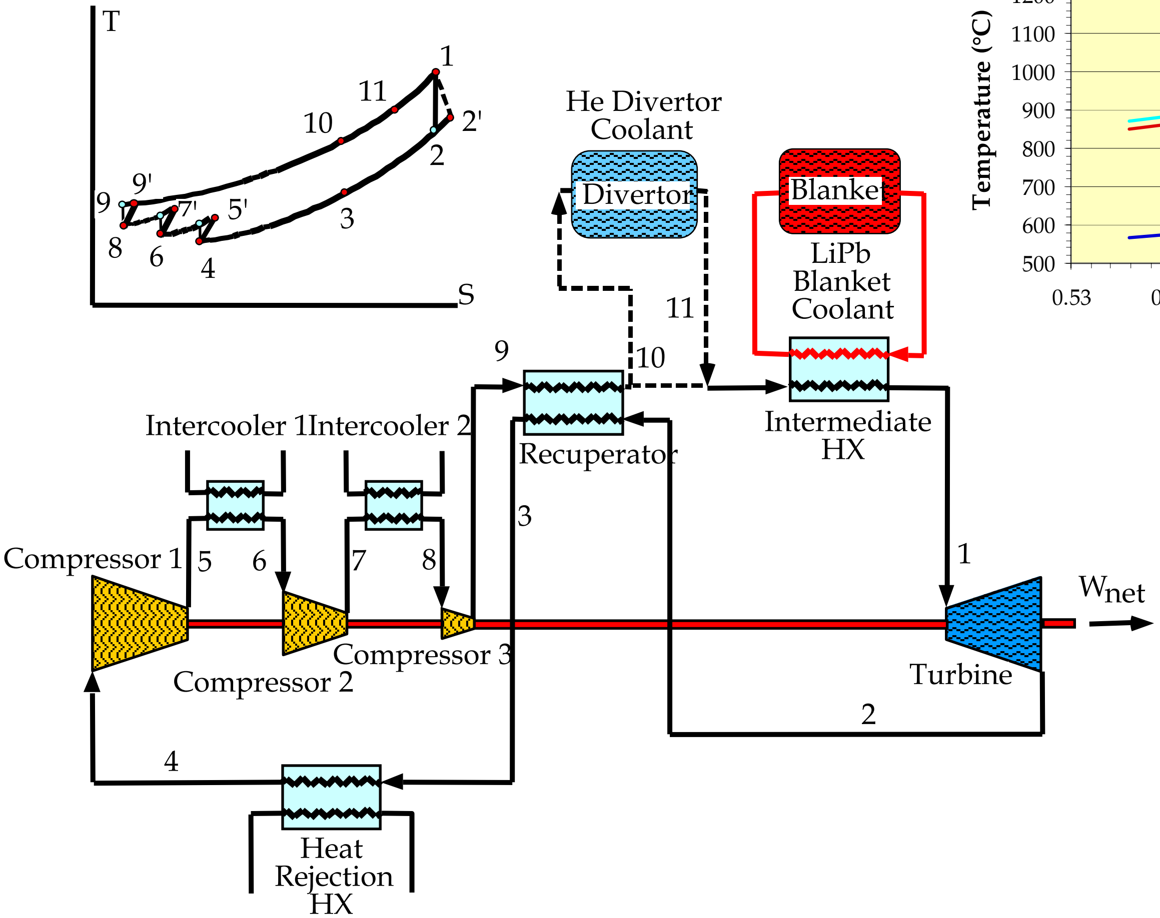
Max. coolant temperature limited by maximum structure temperature

ARIES-ST:
- Dual-cooled ferritic steel with SiC inserts
- Advanced Brayton Cycle at ≥ 650 °C

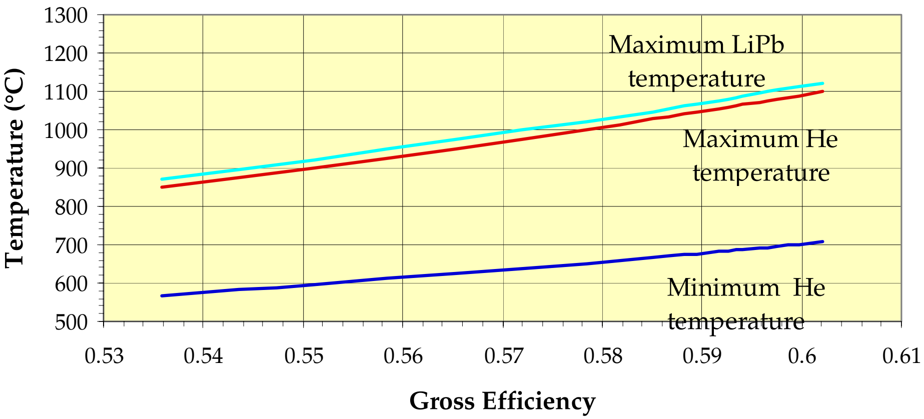
High efficiency with Brayton cycle at high temperature

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*



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



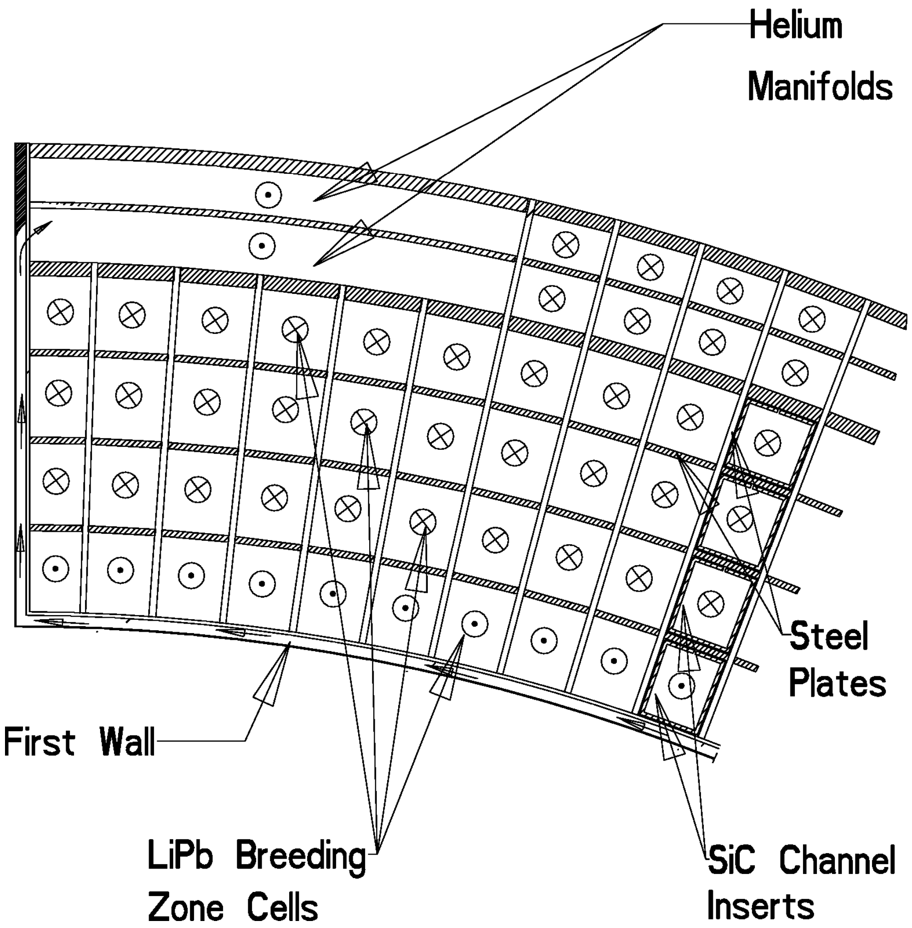
- ➢ Key improvement is the development of cheap, high-efficiency recuperators.

ARIES-ST Features a High-Performance Ferritic Steel Blanket

- Typically, the coolant outlet temperature is limited to the max. operating temperature of structural material (550°C for ferritic steels).
- By using a coolant/breeder (LiPb), cooling the structure by He gas, and SiC insulators, a coolant outlet temperature of 700°C is achieved for ARIES-ST leading to 45% thermal conversion efficiency.

OB Blanket thickness	1.35 m
OB Shield thickness	0.42 m
Overall TBR	1.1

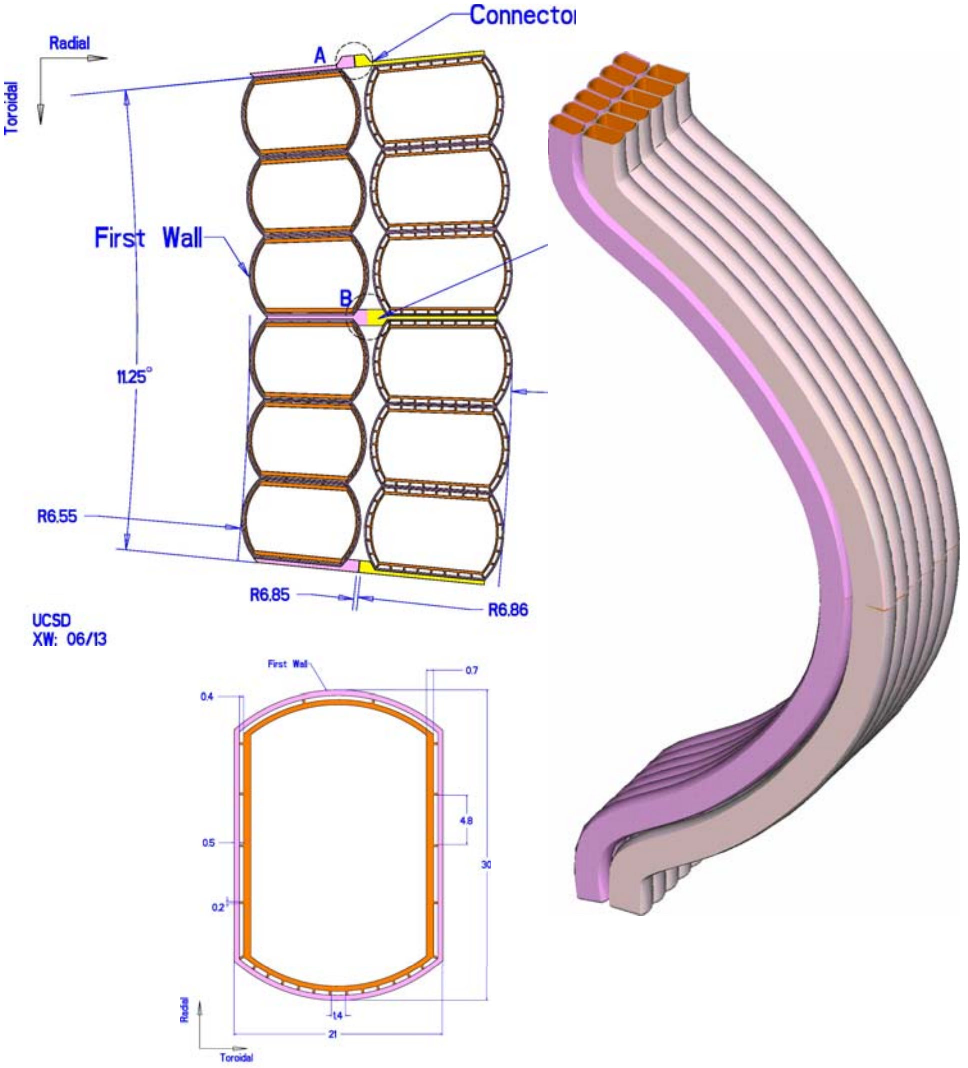
Partial Cross Section of Outboard Blanket



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



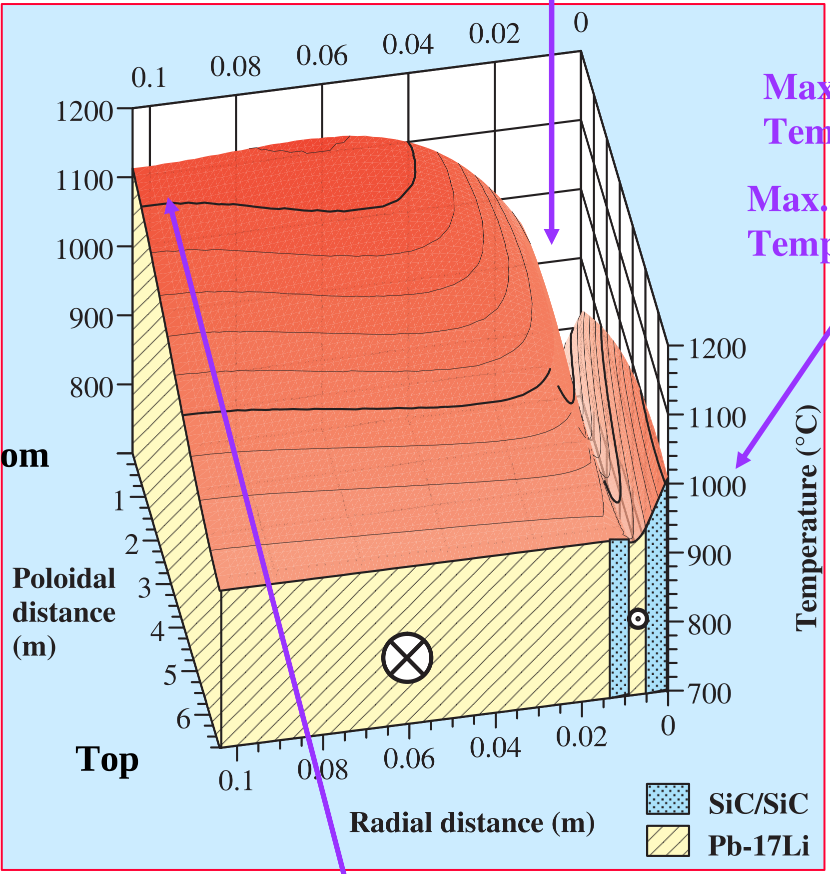
Innovative Design Results in a LiPb Outlet Temperature of 1,100ºC While Keeping SiC Temperature Below 1,000ºC

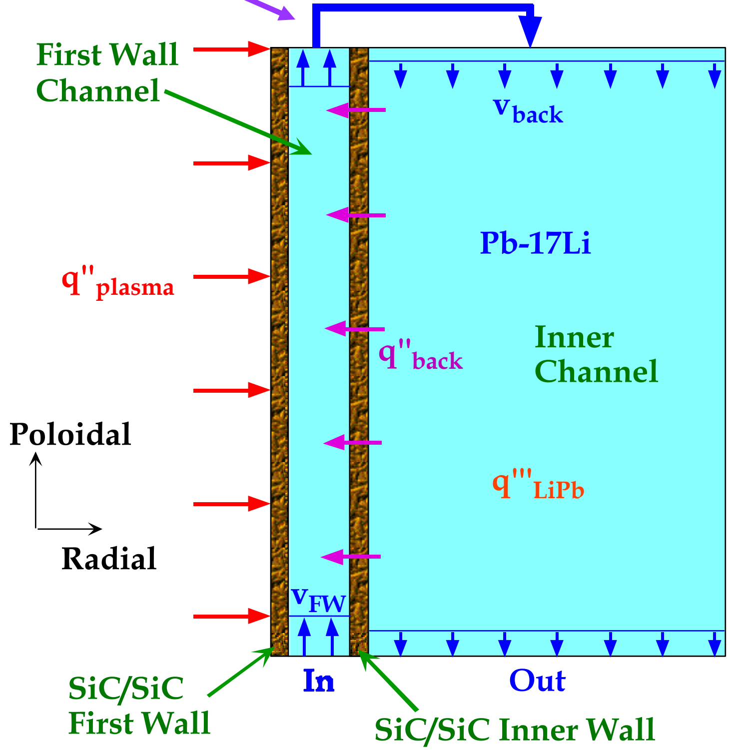
- Two-pass PbLi flow,
  first pass to cool SiC_f/SiC box
  second pass to superheat PbLi

PbLi Inlet Temp. = 764 °C

Max. SiC/SiC Temp. = 996°C

Max. SiC/PbLi Interf. Temp. = 994 °C



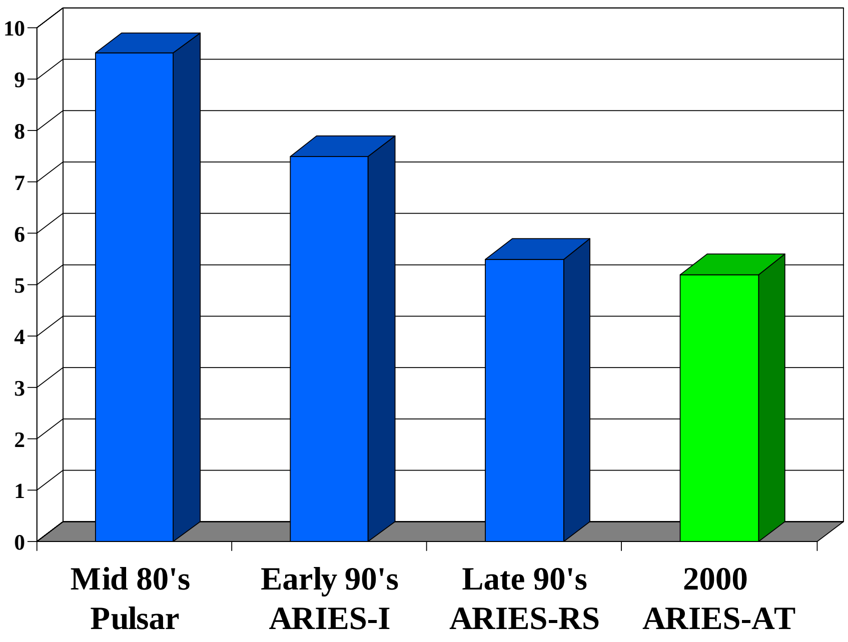


PbLi Outlet Temp. = 1100 °C

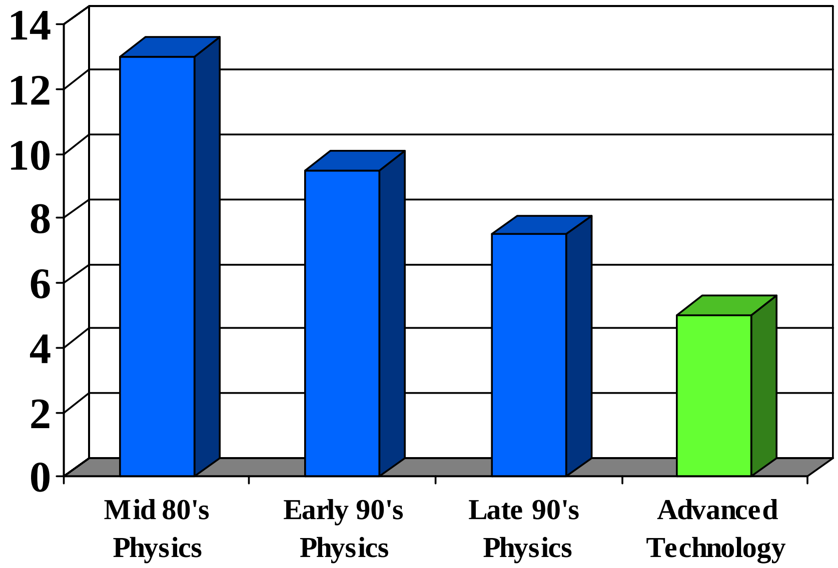
Evolution of the Vision of Fusion Power Plants

3. Attractiveness

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)



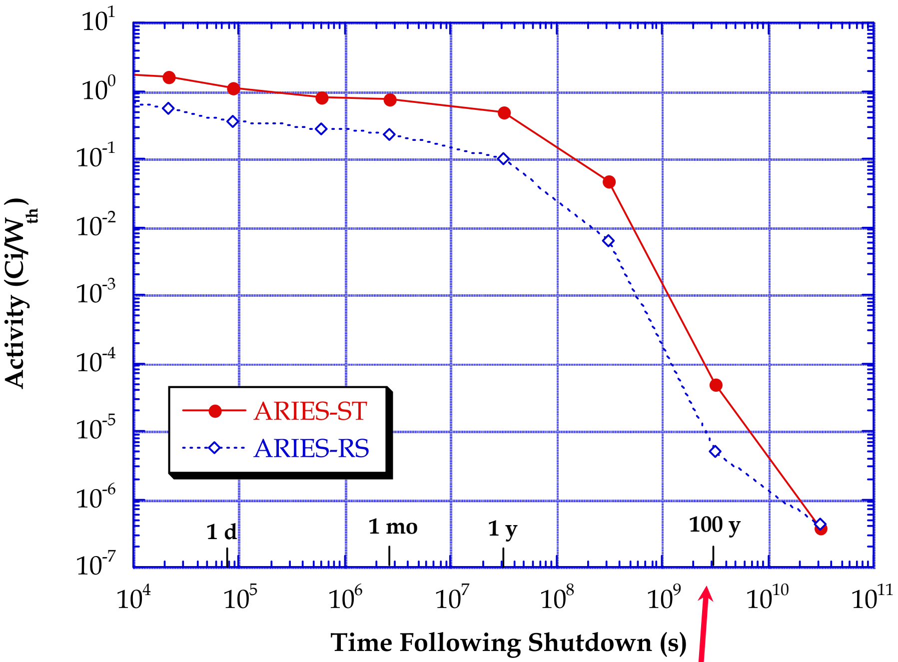
Estimated Cost of Electricity (c/kWh)

Approaching COE insensitive of power density

High Thermal Efficiency

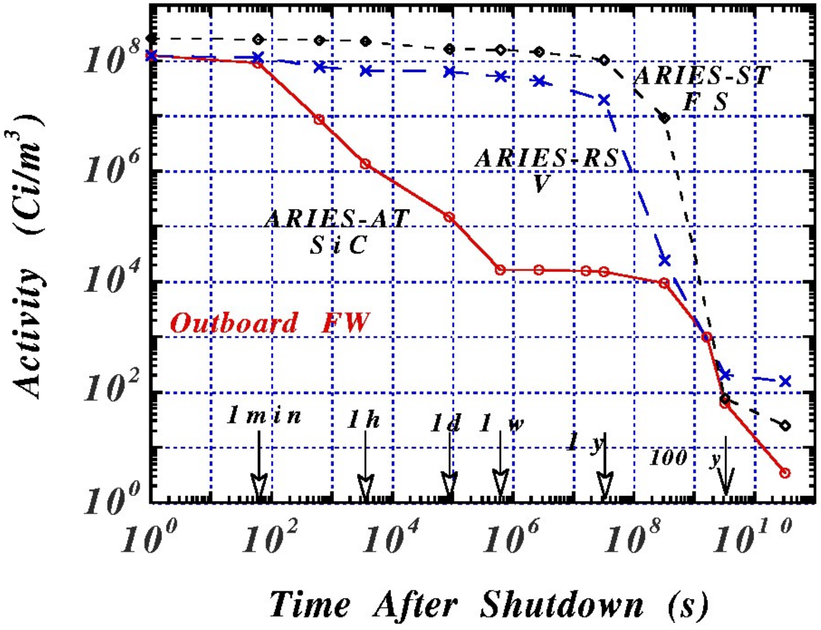
High β is used to lower magnetic field

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.



Evolution of the Vision of Fusion Power Plants

4. Critical R&D Issues

Advances in plasma physics has led to a dramatic improvement in our vision of fusion systems

- ➢ Attractive visions for tokamak exist.
- ➢ The main question is to what extent the advanced tokamak modes can be achieved in a burning plasma:
  - ✓ What is the achievable β_N (macroscopic stability)
  - ✓ Can the necessary pressure profiles realized in the presence of strong a heating (microturbulence & transport)
  - ✓ What is the best regime of operation for the divertor (plasma-material interaction).

- ➢ Attractive visions for ST and stellarator configurations also exist

Fusion "technologies" are the pace setting element of fusion development

- ➢ Pace of "Technology" research has been considerably slower than progress in plasma physics.
- ➢ Most of technology research has been focused on ITER (real technology).
- ➢ R&D in fusion power technologies (fusion engineering sciences) have been limited:
  - ✓ Experimental data is mainly from Europe, but program focus is different.
  - ✓ We need fresh blood, small programs to test concepts, develop data bases, …