# A Design Studies Perspective on Advanced Materials

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International Town Meeting on SiC/SiC Design
and Material Issues for Fusion Systems

January 18-19, 2000
Oak Ridge National Laboratory

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# Outline

1. Review of activities in Advanced Design Studies program
2. Approach for developing an attractive end-product
3. Elaboration of selected design goals:
    - High temperature operation
    - Maintainability
    - Low cost fabrication
    - Safety
4. ARIES designs using SiC/SiC:
    - ARIES-I
    - ARIES-AT
5. Progress in our vision for magnetic fusion systems

# 1. Review of activities in Advanced Design Studies program

# Advanced Design Studies Program Elements

- **Strategic planning and forecasting** – Role of fusion in a sustainable global energy strategy (ORNL, PPPL, PNL, U.Wisc).

- **Design Studies:**

  National power plant studies team (ARIES).

  - Neutron source study;
  - ARIES-AT;
  - Integrated analysis of IFE chambers.

  Pre-conceptual designs and analysis of critical issues of advanced fusion concepts.

# National Power Plant Studies Program Initiated Two-year Projects in 1/99

- **Fusion Neutron Source Study:**
    - Non-electric applications of fusion, especially those resulting in near-term products, may lead to new clients and additional resources for fusion.
    - An assessment phase is underway to identify promising concepts and provide necessary information for proceeding further.
- **ARIES-AT:**
    - Assess impact of advanced technologies as well as new physics understanding & modeling capabilities on the performance of advanced tokamak power plants.
- **Integrated IFE Chamber Study (to start in 2000):**
    - Identify and explore design window for IFE chambers.

# Non-Electric Applications of Fusion Neutrons

- Typical applications (~$10^{19}$-$10^{21}$ n/s):
  - Transmutation of fission waste;
  - Hybrids for fuel and/or energy production;
  - Fusion materials and engineering testing.
- Post-cold-war additions:
  - Tritium production;
  - Burning of plutonium from dismantled weapons.
- Recent application (~$10^{11}$-$10^{13}$ n/s)
  - Radioisotope production;
  - Medical radiotherapy;
  - Detection of explosives.

Focus Areas

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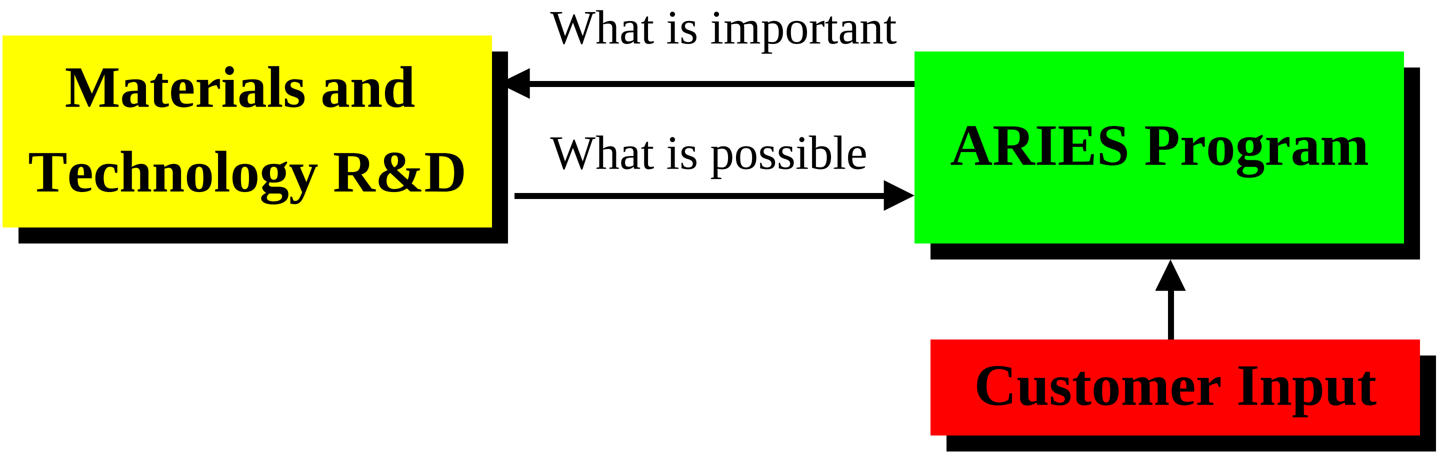
# 2. Approach for developing an attractive end-product

# Conceptual Designs of Magnetic Fusion Power Systems Are Developed Based on a Reasonable Extrapolation of Physics & Technology

- Plasma regimes of operation are optimized based on latest experimental achievements and theoretical predictions.
- Engineering system design 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.



What is important

**Materials and Technology R&D**

What is possible

**ARIES Program**

**Customer Input**

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

- **Requirements:**

- **Have an economically competitive life-cycle cost of electricity, *e.g.*,**

  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.**

# Requirements translate into specific design parameters via integrated design studies, involving numerous trade-offs.

## Example allocation of economic goals to meet COE target

| | |
|---|---|
| • Capital cost | <$5 B |
| • Annual operating & maintenance cost | <$120 M |
| • Plant availability | >87% |
| • Gross thermal efficiency | >46% |
| • Recirculating power | <15% of gross |
| • Construction and licensing period | <5 yr |

**Trade-offs:**

- High-performance structural materials usually cost more
- High power density leads to faster “burnup”, hence lower availability
- High power density leads to lower coolant temperature and $\eta$

# Optimization Strategy for ARIES-AT

**Capital Cost** $\Sigma\, c_i\, M_i + \Sigma\, c_k\, P_k$

## Previous Emphasis:

- Reduce recirculating power (maximize bootstrap current).
- Reduce mass of fusion core ($M_i$) by increasing fusion power density (higher performance physics and higher performance magnets).

## Additional New Emphasis:

- Minimize thermal power by maximizing thermal conversion efficiency (high-temperature blanket utilizing Brayton cycle).
- Enhance availability with improved maintenance concepts
- Reduce the unit cost of components, $c_i$ and $c_k$ :
  - Use advanced manufacturing techniques;
  - High level of safety assurance allows a smaller nuclear boundary;
- Trade off performance versus unit costs.

# 3. Elaboration of selected design goals

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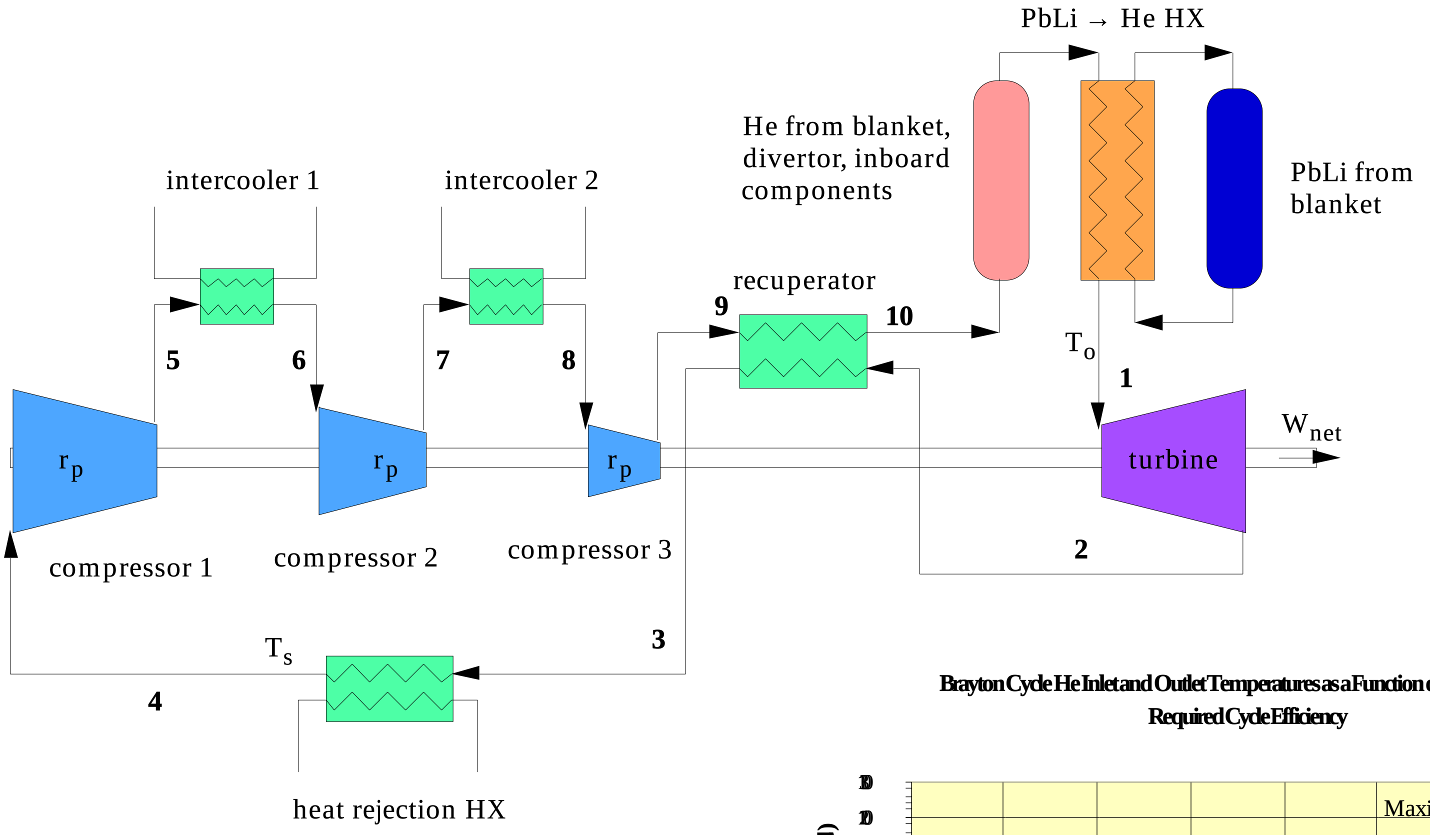
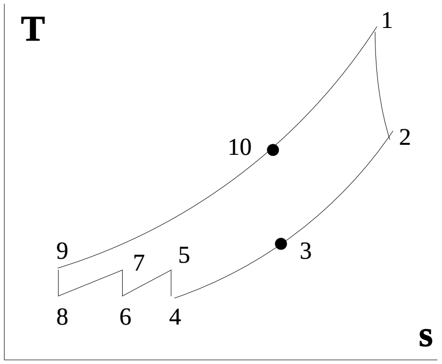
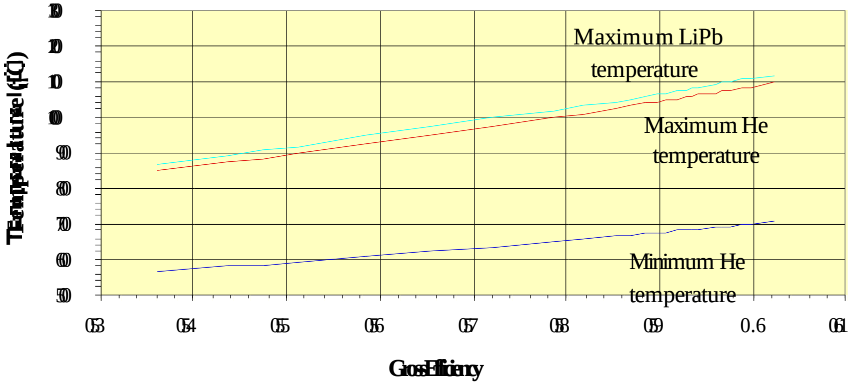
# Advances in Brayton Cycle Components Can Lead to Higher Efficiency





- Key improvements include the development of cheap, high-efficiency recuperators and other high-temperature power cycle components

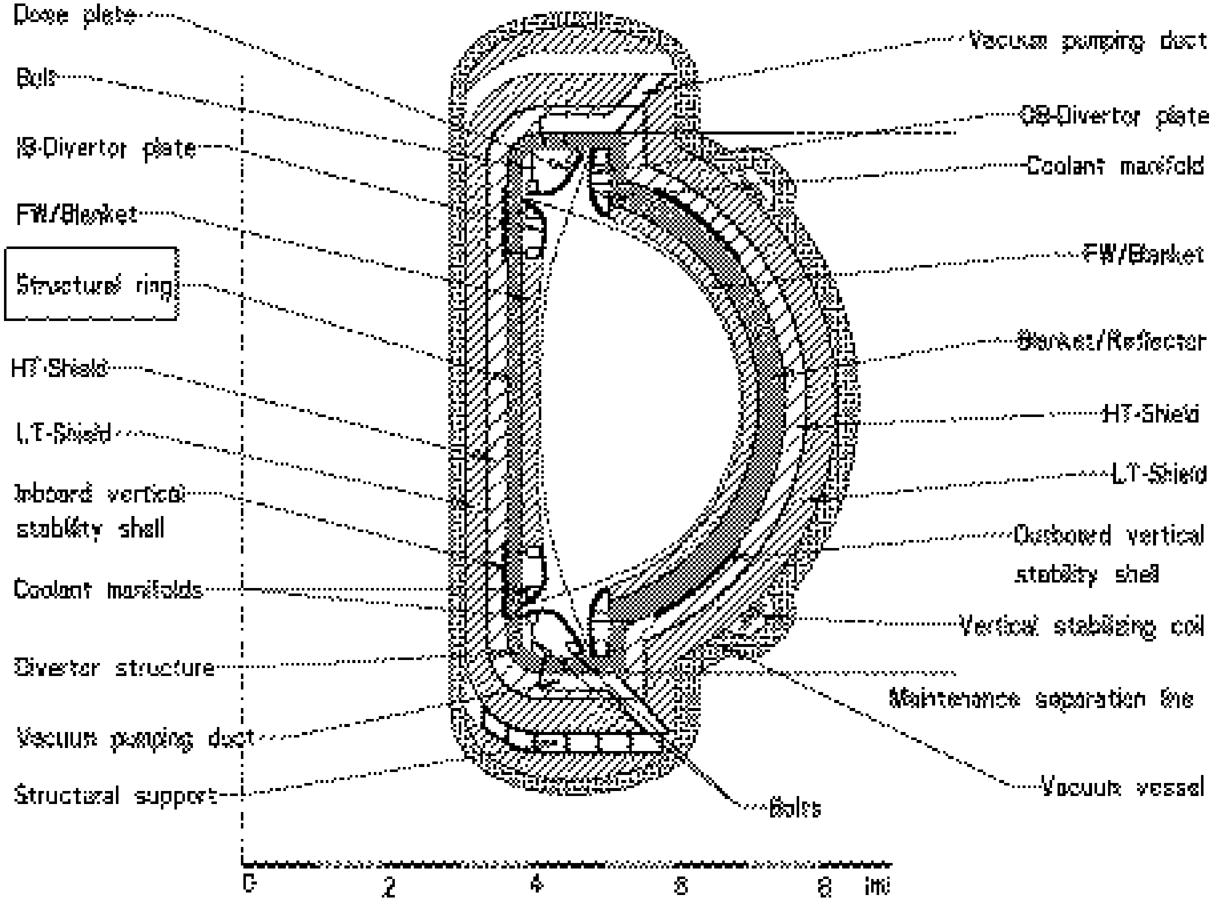
**Brayton Cycle He Inlet and Outlet Temperatures as a Function of Required Cycle Efficiency**



# The ARIES-RS Replacement Sectors are Integrated as a Single Unit for High Availability

## Key Features

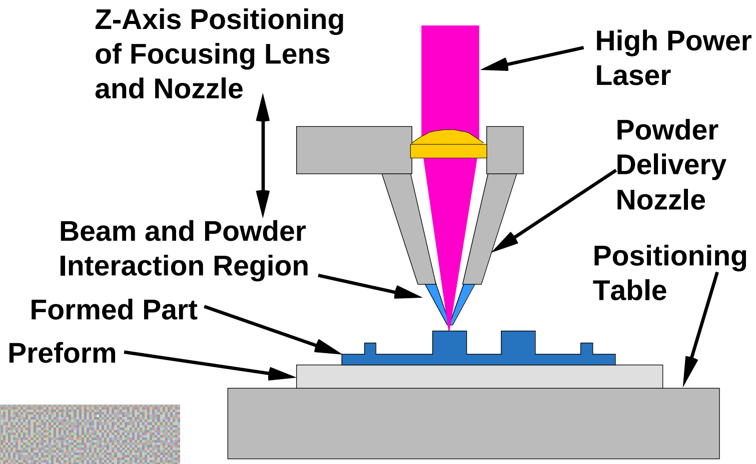
- No in-vessel maintenance operations
- Strong poloidal ring supporting gravity and EM loads.
- First-wall zone and divertor plates attached to structural ring.
- No rewelding of elements located within radiation zone
- All plumbing connections in the port are outside the vacuum vessel.

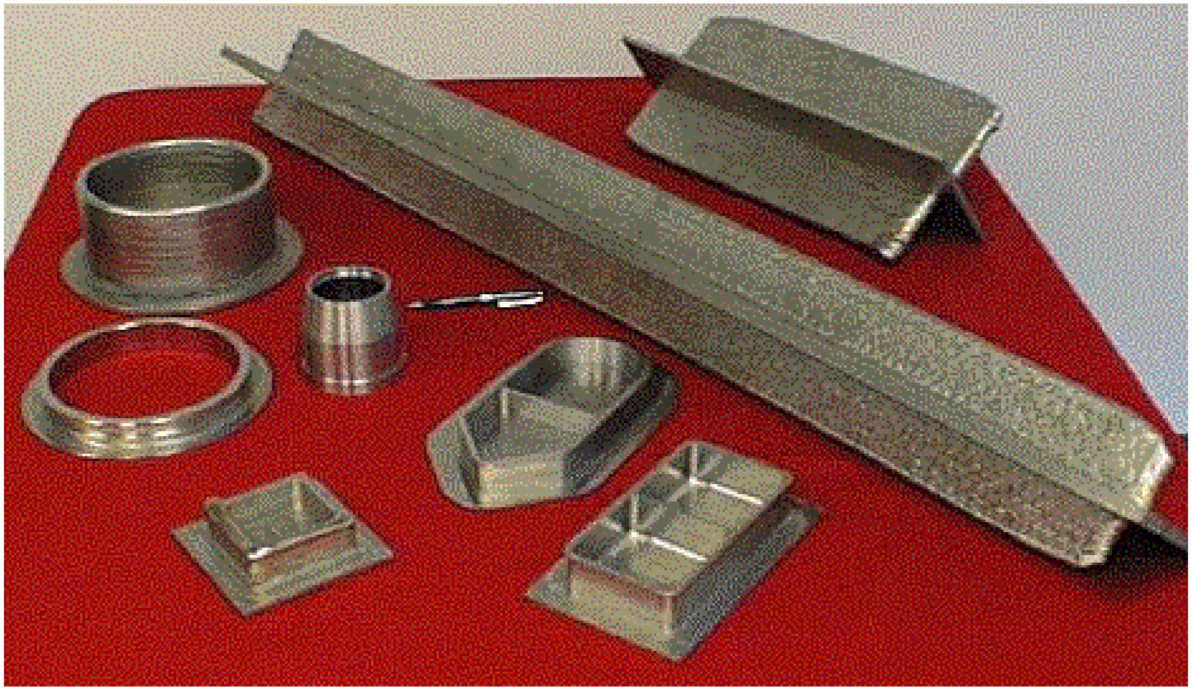


# Laser or Plasma Arc Forming

- A laser or plasma-arc deposits a layer of metal (from powder) on a blank to begin the material buildup
- The laser head is directed to lay down the material in accordance with a CAD part specification

**Schematic of Laser Forming Process**





**AeroMet has produced a variety of titanium parts as seen in attached photo. Some are in as-built condition and others machined to final shape. Also see Penn State for additional information.**

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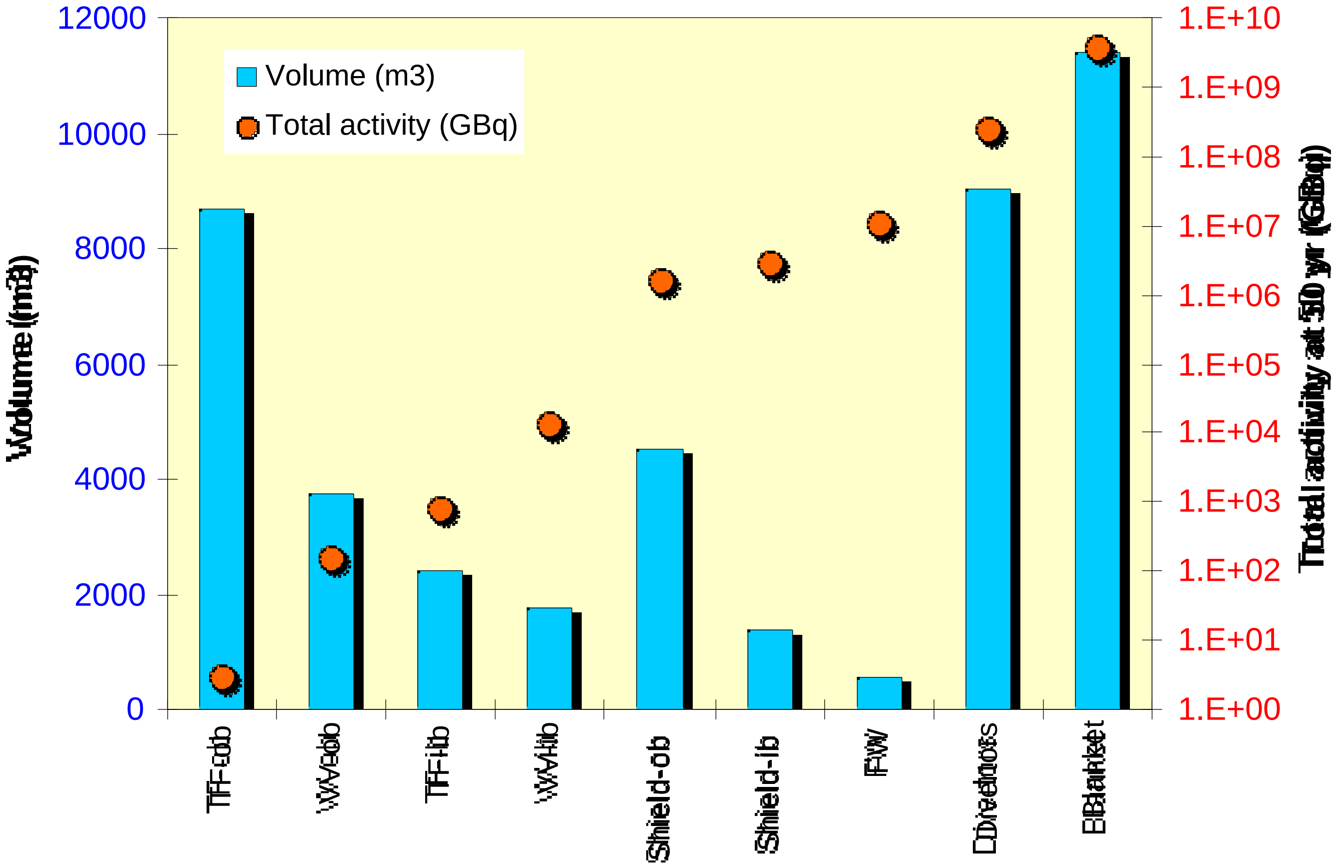
# There is a large volume of low level radioactivity in a fusion plant: *52% of the volume contains only 0.11% of the total activity*



Data from analyses in phase 2 of the European Safety and Environmental Assessment of Fusion Power, (SEAFP-2).

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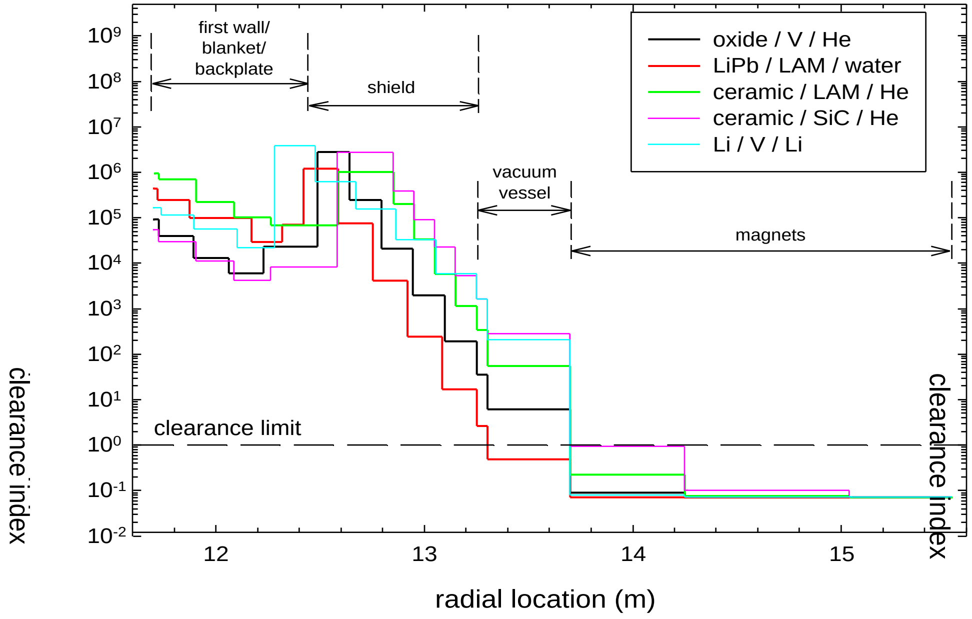
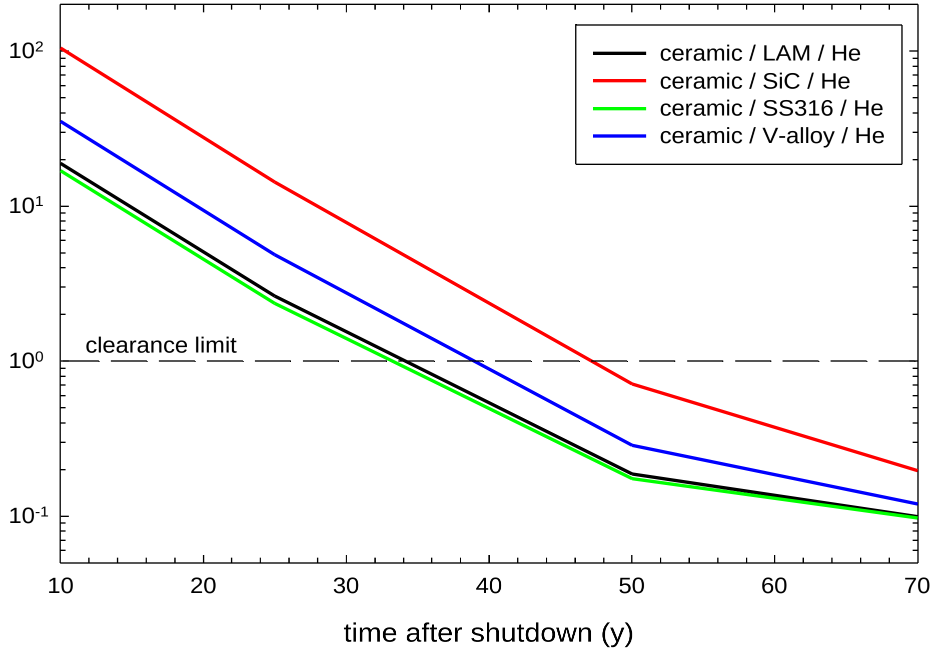
# Different combinations of FW/Blanket materials result in different levels of ex-vessel activation, as measured by the clearance index

Clearance index versus radial location for different design options

Influence of FW and Blanket Structural Material on Time to Meet Clearance Limit for TF Coil Case





**Note:** although the SiC/ceramic/He design has least activation (lowest clearance index) in FW and blanket, it has the greatest activation (highest clearance index) in ex-vessel components and results in the longest time to clear the TF coil case

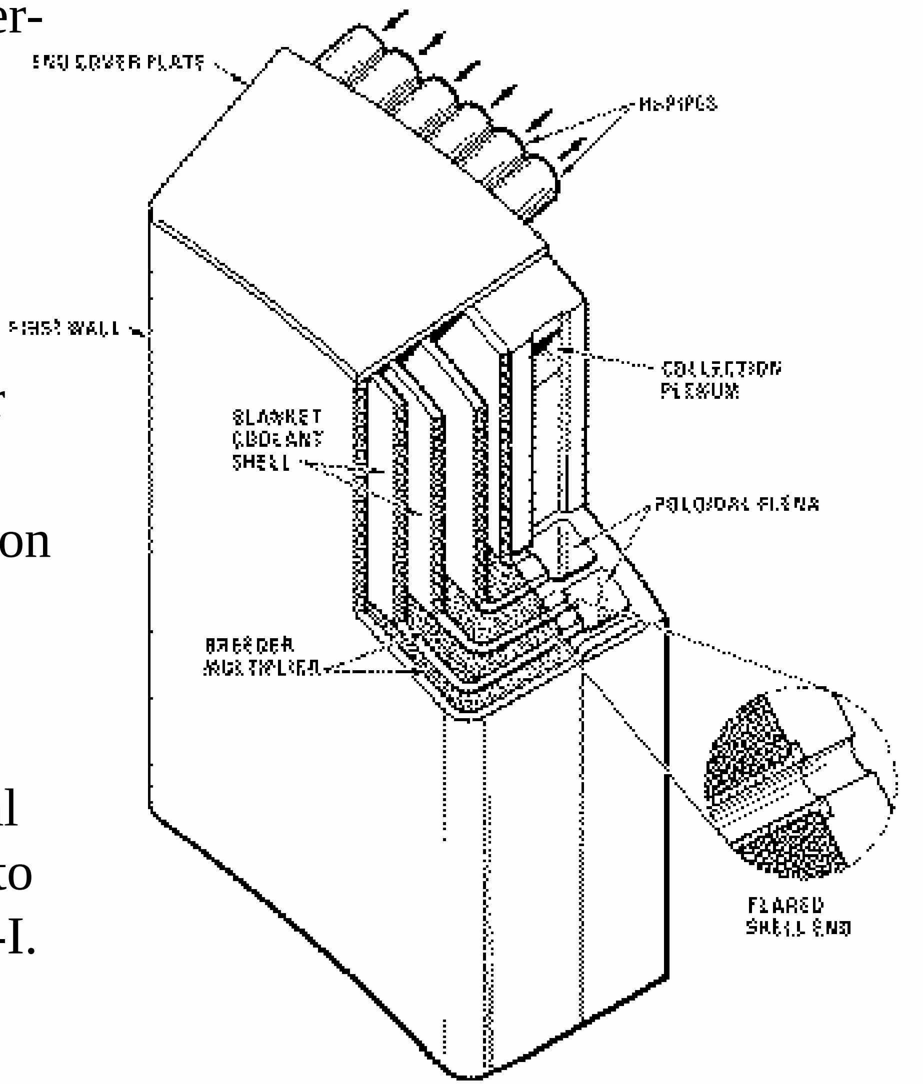
# 4. ARIES designs using SiC/SiC

# The ARIES Team Has Examined Several Magnetic Fusion Concept as Power Plants in the Past 10 Years

- TITAN reversed-field pinch (1988)
- ARIES-I first-stability tokamak (1990)
- ARIES-III D-$^3$He-fueled tokamak (1991)
- ARIES-II and -IV second-stability tokamaks (1992)
- Pulsar pulsed-plasma tokamak (1993)
- SPPS stellarator (1994)
- Starlite study (1995) (goals & technical requirements for power plants & Demo)
- ARIES-RS reversed-shear tokamak (1996)
- ARIES-ST spherical torus (1999)
- ARIES-AT advanced tokamak (ongoing)

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

- Excellent safety & environmental characteristics (very low activation and 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.
- Pulsar, ARIES-IV also adopted SiC/SiC



# 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.
- **Higher Performance Magnets:** High-$T_c$ superconductors.

  Present strawman operates at the same power density as ARIES-RS; higher β was used to reduce the peak field at the magnet.
- Reduce unit cost of components through **Advanced Manufacturing Techniques.**

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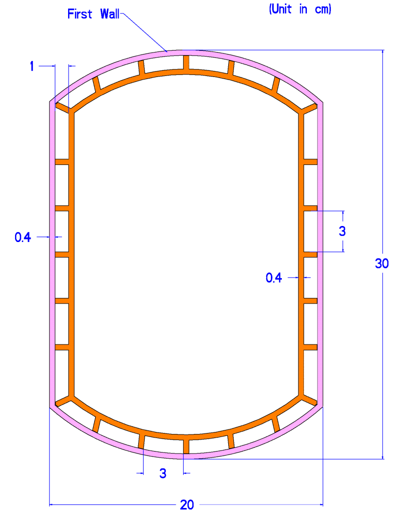
# ARIES-AT: Physics Highlights

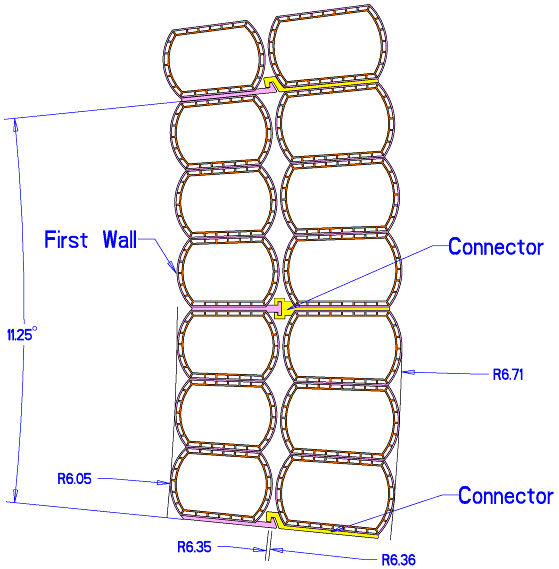
- Use the lessons learned in ARIES-ST optimization to reach a higher performance plasma;
  - Using > 99% flux surface from free-boundary plasma equilibria rather than 95% flux surface used in ARIES-RS leads to larger elongation and triangularity and higher stable β.
- Eliminate HHFW current drive and use only lower hybrid for off-axis current drive.
- Perform detailed, self-consistent analysis of plasma MHD, current drive and divertor (using finite edge density, finite p′, impurity radiation, *etc*.) (In progress)
- ARIES-AT blanket allows vertical stabilizing shell closer to the plasma, leading to higher elongation and higher β. (In progress)

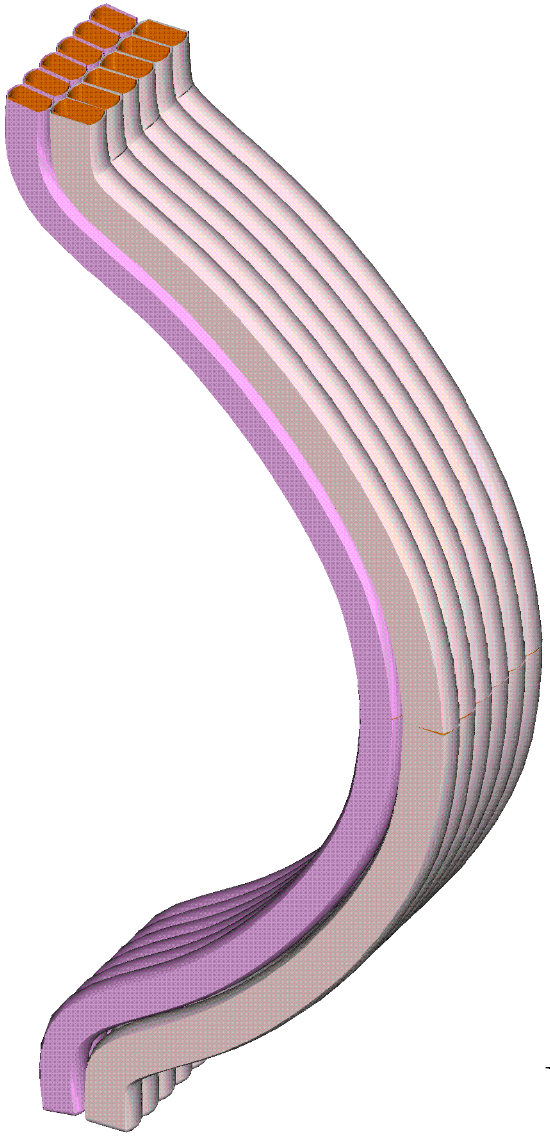
# ARIES-AT: SiC Composite Blanket

## Outboard blanket & first wall

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- High LiPb outlet temperature (~1100$^{o}$C) and high thermal efficiency of ~60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.







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# Summary

- SiC/SiC composites offer compelling advantages for fusion:
  - Very high thermal conversion efficiency
  - Very attractive safety and waste characteristics
- The net benefit in an integrated system depends on many factors.
- Important questions remain to be answered for SiC/SiC:
  - Limitations on power density:
    - *E.g.*, maintaining adequate thermal conductivity and strength under irradiation
    - MHD heat transfer
  - Compatibility with coolant at elevated temperature
  - Component lifetime and reliability
  - Cost of ex-vessel components (SiC in FW/B/S costs only $26M @$400/kg)
  - Other implications of a ceramic power core:
    H&CD, plasma stability, HX, divertor…

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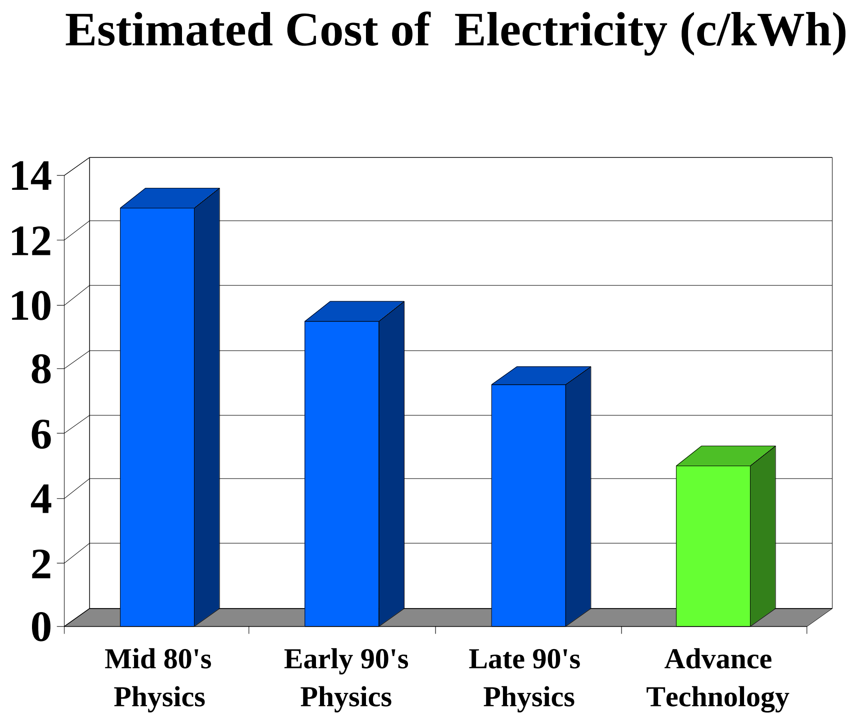
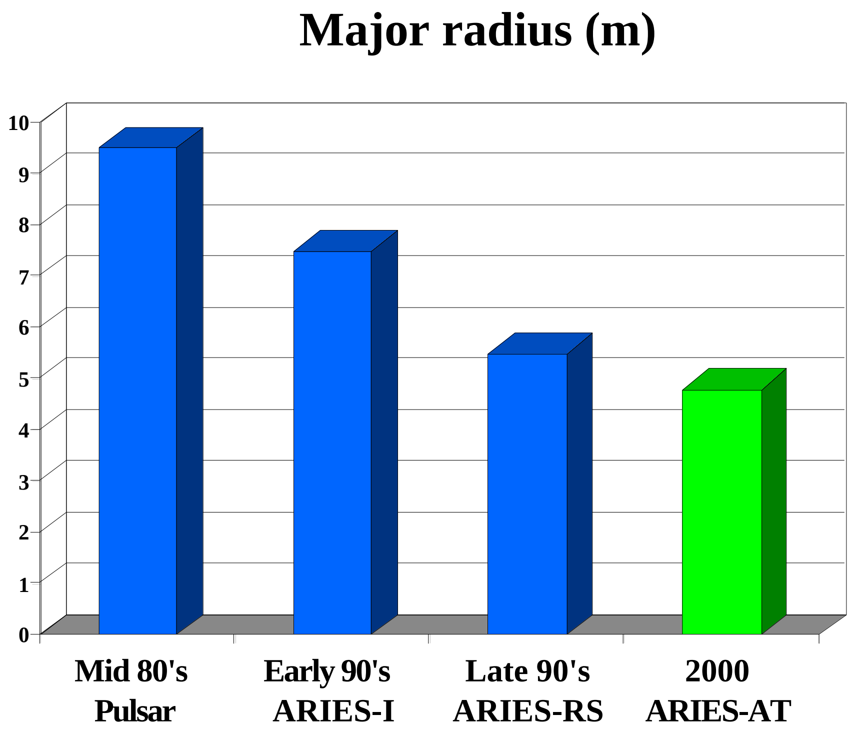
# Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and is Directly Tied to Advances in Fusion Science & Technology


**Estimated Cost of Electricity (c/kWh)**


**Major radius (m)**

**Preliminary ARIES-AT parameters**:

| | | | |
|---|---|---|---|
| Major radius: | 4.8 m | Fusion Power | 1,740 MW |
| Toroidal b: | 6.4% | Net Electric | 1,000 MW |
| Wall Loading: | 4.3 MW/m$^2$ | COE | 5 c/kWh |