Overview of the ARIES Program

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IAP Short Course

A Modern View of Fusion Power Plants: Progress and Prospects

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Massachusetts Institute of Technology

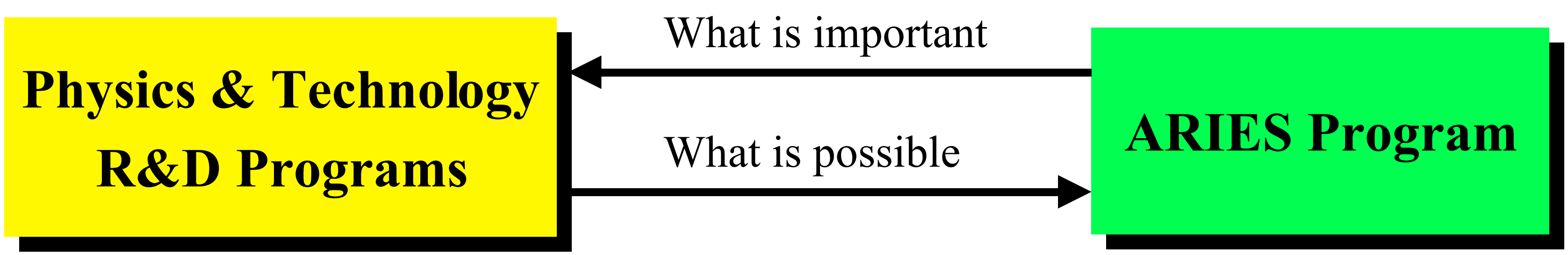
Outline

- ➢ **Mission and organization**
- Making the case for fusion
- Recent power plant studies
- Advances in physics and technology
- Progress and prospects

ARIES is the Primary Venue in the US for Conceptual Design & Assessment of Fusion Power Plants

- **Mission Statement:**

  Perform advanced integrated design studies of the long-term fusion energy embodiments to identify key R&D directions and provide visions for the program.



Systems studies are performed to identify not just the most effective experiments for the moment, but also the most cost-effective routes to the evolution of the experimental, scientific and technological program.

The National ARIES Program Allows Fusion Scientists to Investigate Fusion Systems as a Team

- Universities (~2/3), national laboratories, and private industry contribute.
- A typical team member spends ~25% of his time on this activity.
- Decisions are made by consensus.
- The team is flexible: expert groups and advocates are involved as needed to ensure the flow of information to/from R&D programs.

ARIES-AT Participants:

Argonne National Laboratory	**Boeing High Energy Systems**
General Atomics	**Idaho National Eng. & Environmental Lab.**
Massachusetts Institute of Technology	**Princeton Plasma Physics Laboratory**
Rensselaer Polytechnic Institute	**University of Wisconsin - Madison**
Forschungszentrum Karlsruhe	**University of California, San Diego**

Because it draws its expertise from the national program, ARIES is unique in the world in its ability to provide a fully integrated analysis of power plant options including plasma physics, fusion technology, economics, safety, etc.

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.
- Program continuity allows concept comparisons on an even playing field.

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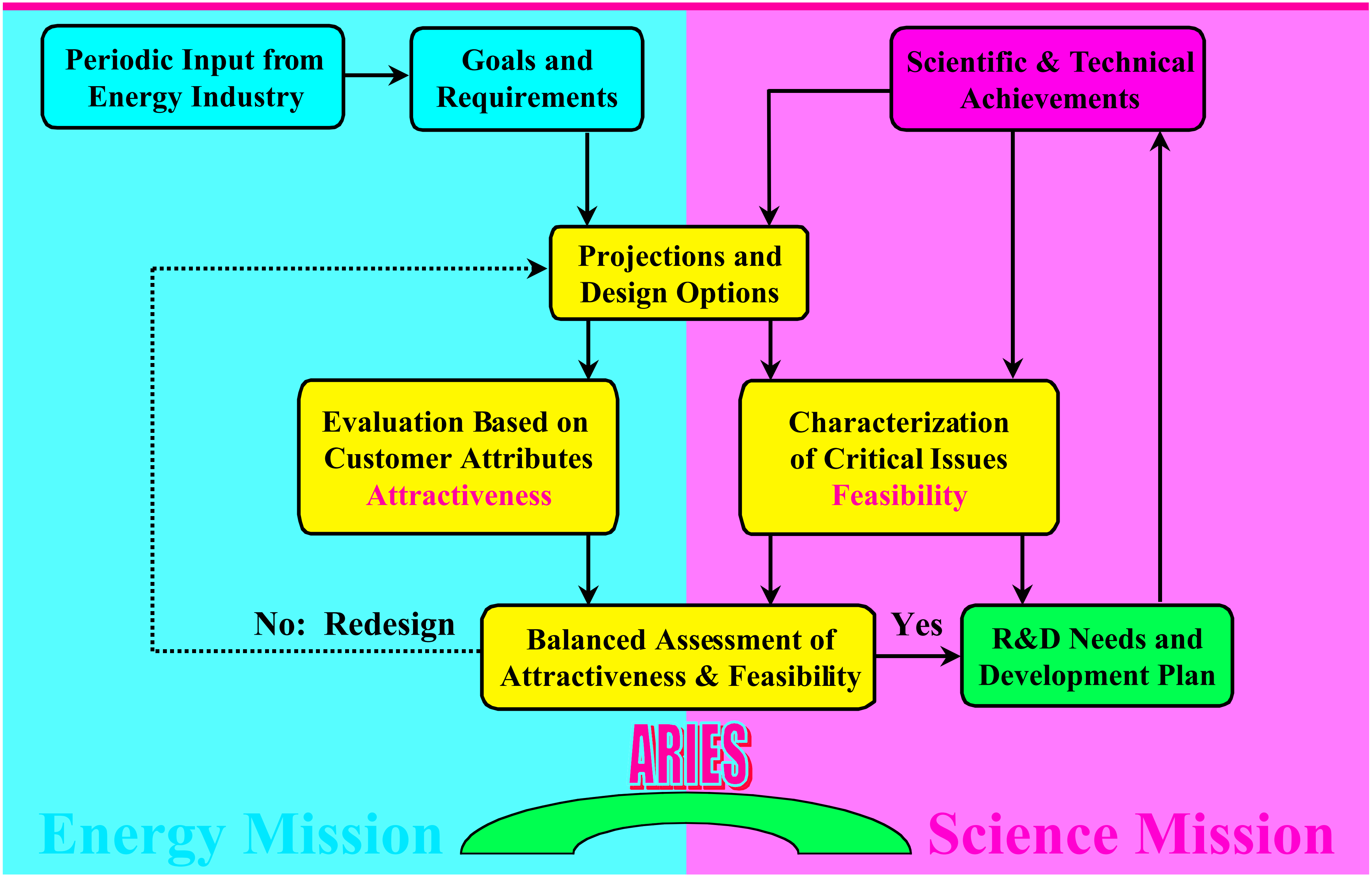
ARIES Research Framework:
Assessments Based on Attractiveness & Feasibility



Fusion must demonstrate that it can be a safe, clean, & economically attractive option

- **Gain Public acceptance:**
  - ∗ 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.
- **Have an economically competitive life-cycle cost of electricity:**
  - ∗ Low recirculating power;
  - ∗ High power density;
  - ∗ High thermal conversion efficiency;
  - ∗ Less expensive systems.

Top-Level Requirements for Commercial Power Plants Were Developed through Interaction with Representatives from U.S. Electric Utilities and the Energy Industry

- 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;
- 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.

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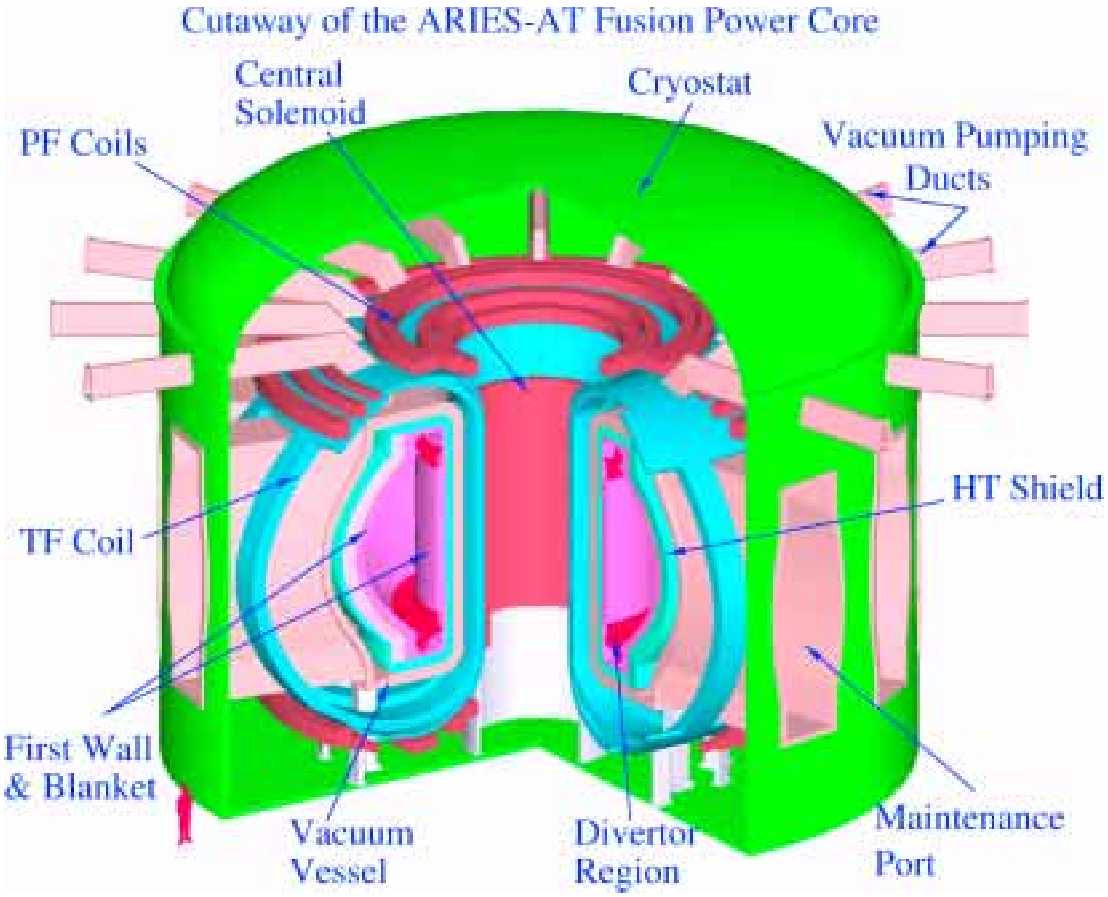
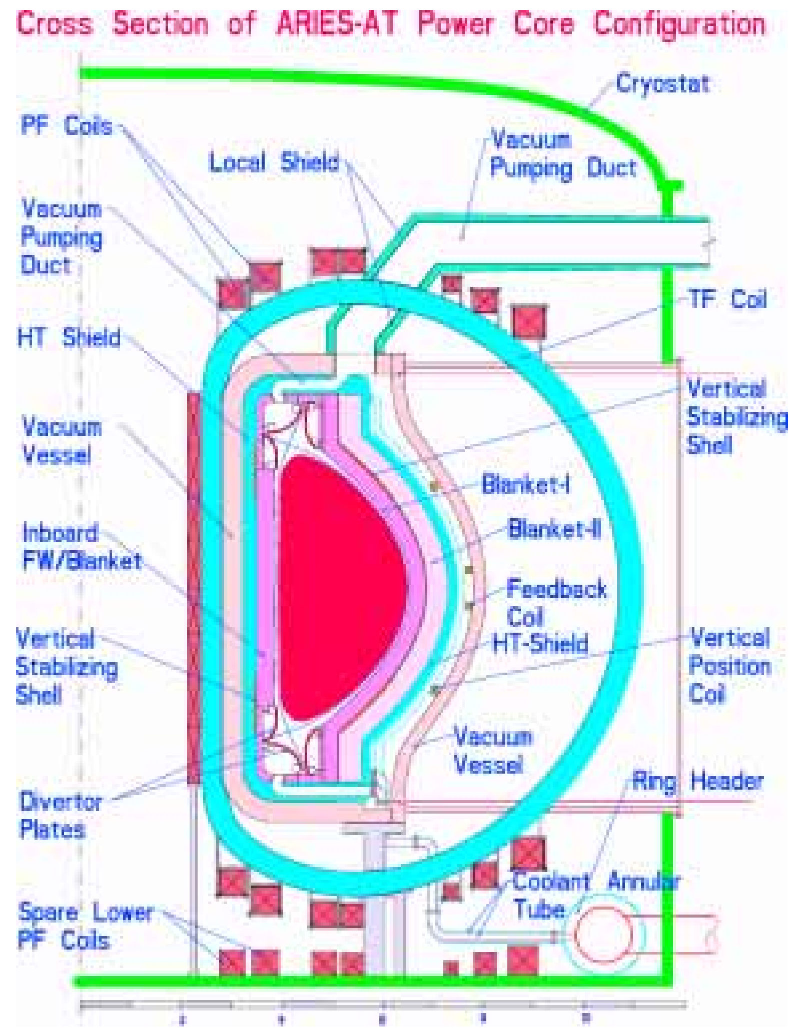
The ARIES Team Has Examined Several Magnetic Fusion Concepts as Power Plants in the Past 12 Years

- 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)
- Fusion neutron source study (2000)
- ARIES-AT^2 advanced technology and advanced tokamak (2000)
- IFE chamber assessment (ongoing)

ARIES-RS and ARIES-AT are conceptual 1000 MWe power plants based on reversed-shear tokamak plasmas





Key Performance Parameters of ARIES-RS

	Design Feature	Performance Goal
Economics:		
Power Density	Reversed-shear Plasma Radiative divertor Li-V blanket with insulating coatings	Wall load: 5.6/4.0 MW/m^2 Surface heat flux: 6.0/2.0 MW/m^2
Efficiency	610^o C outlet (including divertor) Low recirculating power	46% gross efficiency ~90% bootstrap fraction
Lifetime	Radiation-resistant V-alloy	200 dpa
Availability	Full-sector maintenance Simple, low-pressure design	Goal: 1 month < 1 MPa
Safety:	Low afterheat V-alloy No Be, no water, Inert atmosphere	< 1 rem worst-case off-site dose (no evacuation plan)
Environmental attractiveness:	Low activation material Radial segmentation of fusion core	Low-level waste (Class-A) Minimize waste quantity

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

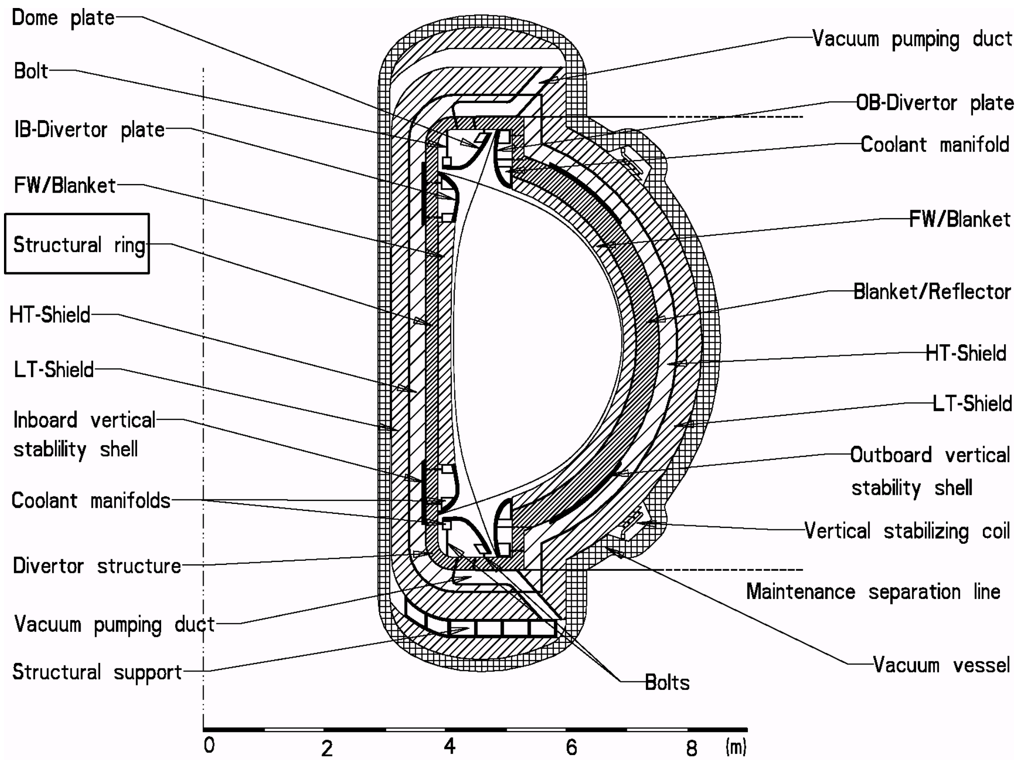
	ARIES-RS Performance	ARIES-AT Goals
Economics		
Power Density	Reversed-shear Plasma Radiative divertor Li-V blanket with insulating coatings	Higher performance RS plasma, SiC composite blanket High T_c superconductors
Efficiency	610^{o}C outlet (including divertor) Low recirculating power	> 1000 ^{o}C 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

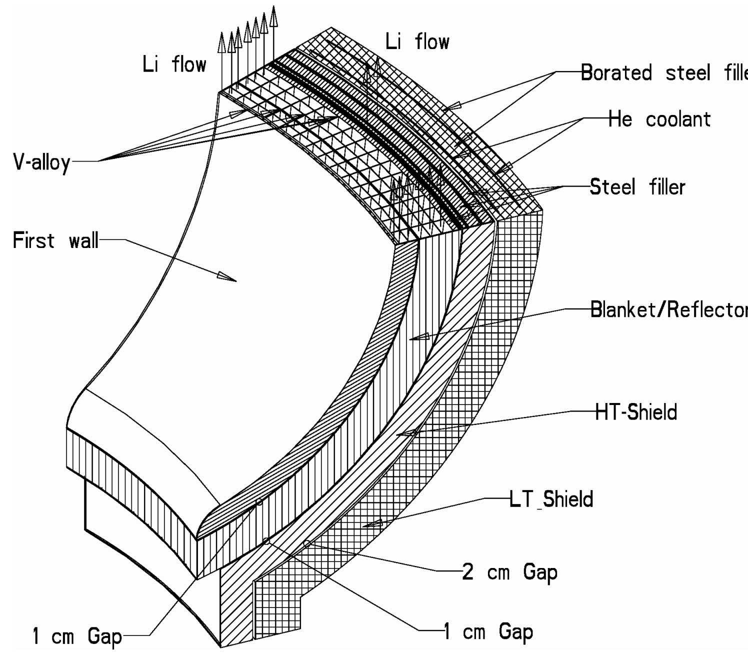
Major Parameters of ARIES-RS and ARIES-AT

	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
Toroidal β	5%*	**9.2%***
Normalized β_N	4.8*	5.4*
Plasma elongation (κ_x)	1.9	**2.2**
Plasma current	11	13
Peak field at TF coil (T)	16	**11.4**
Peak/Avg. neutron wall load (MW/m^2)	5.4/4	4.9/3.3
Thermal efficiency	0.46	**0.59**
Fusion power (MW)	2,170	**1,755**
Current-drive power to plasma (MW)	81	**36**
Recirculating power fraction	0.17	0.14
Cost of electricity (¢/kWh)	7.5	5.

* *Designs operate at 90% of maximum theoretical β limit.*

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



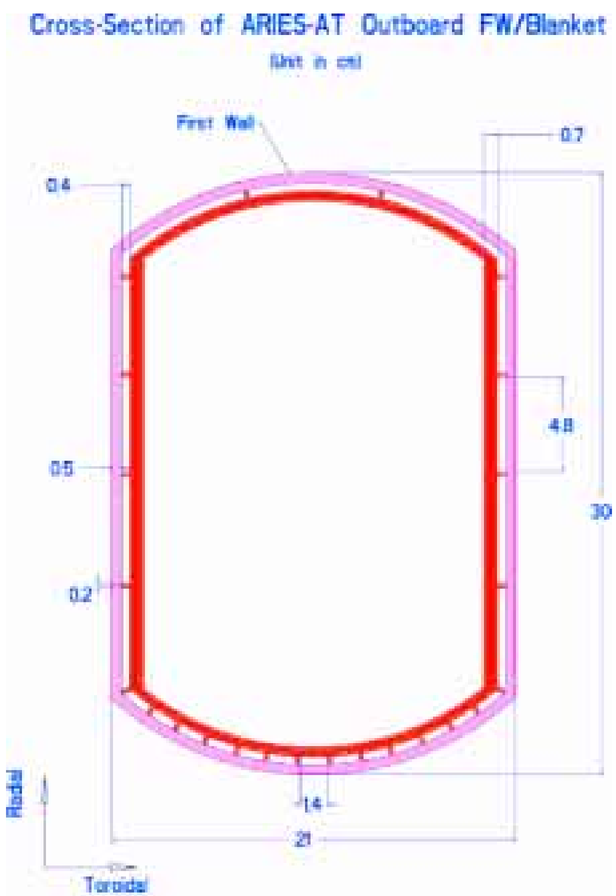


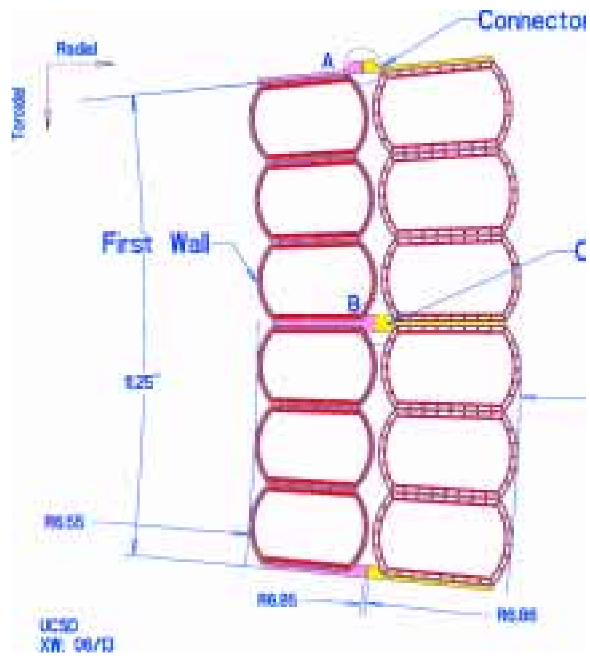
Key Features:

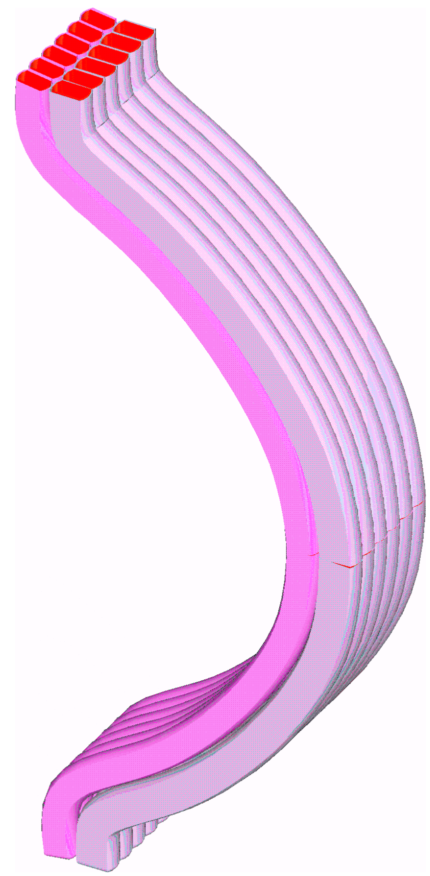
- No in-vessel maintenance operations
- Strong poloidal ring supporting gravity and EM loads.
- First-wall zone and divertor plates attached to structural ring.
- No rewelding of elements located within radiation zone
- All plumbing connections in the port are outside the vacuum vessel.

The ARIES-AT Blanket Utilizes a 2-Pass Coolant to Uncouple Structure from Outlet Coolant Temperature

- **2-pass Pb-17Li flow, first pass to cool SiC/SiC box and second pass to “superheat” Pb-17Li**
- **Maintain blanket SiC/SiC temperature (~1000°C) < Pb-17Li outlet temperature (~1100°C)**







Spherical Tokamak Options

Fusion development devices (*e.g.*, neutron sources):

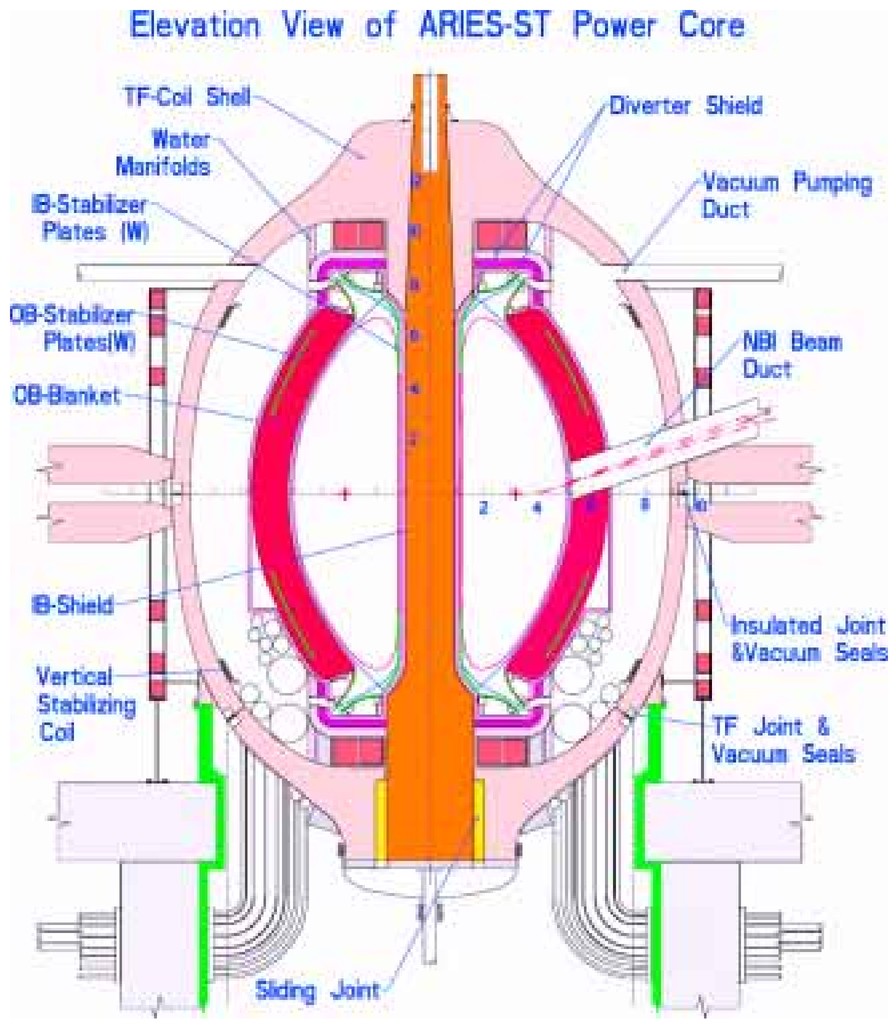
- Modest size machines can produce significant power;
- Planned experiments should establish the physics basis.

Power plants:

- Recirculating power fraction (mainly Joule losses in the center-post) is the driving force.
  Design strategy: Maximize plasma beta and minimize the distance between plasma and center-post.

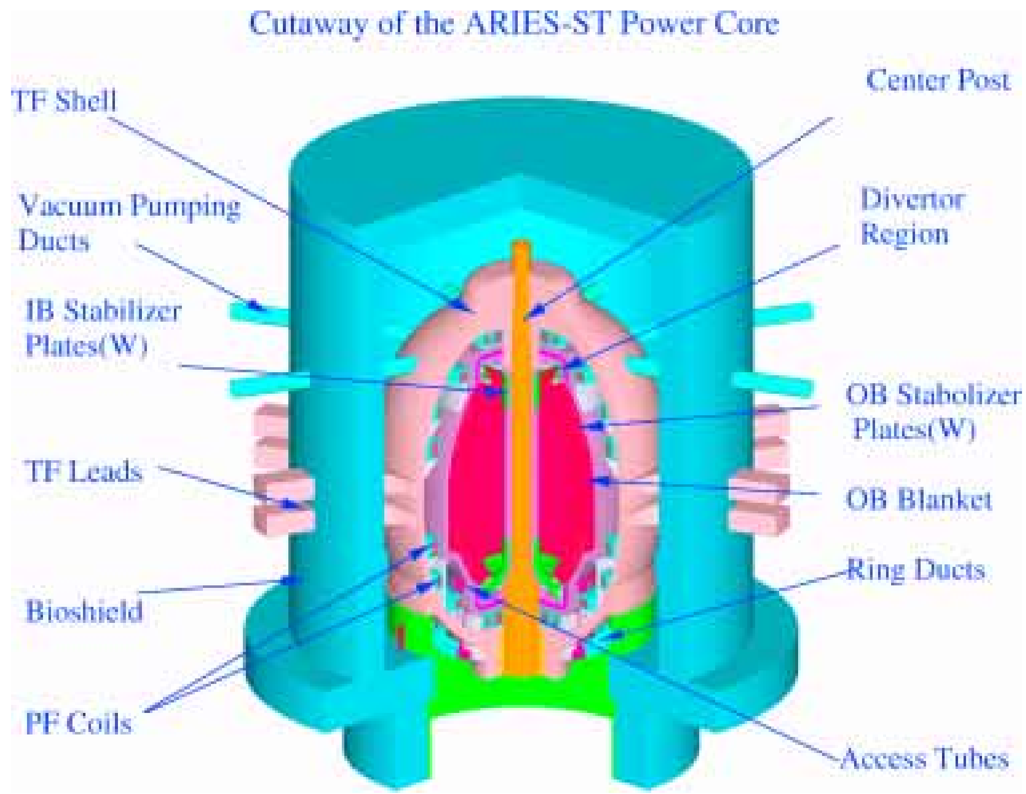
The ARIES-ST Study Identified Key Directions for Spherical Tokamak Research

- Substantial progress was made towards optimization of ST equilibria with >95% bootstrap fraction:
  - $\beta = 54\%$, $\kappa = 3$;
- A feasible center-post design has been developed;
- Several methods for start-up has been identified;
- Current-drive options are limited;
- 1000-MWe ST power plants are comparable in size and cost to advanced tokamak power plants.



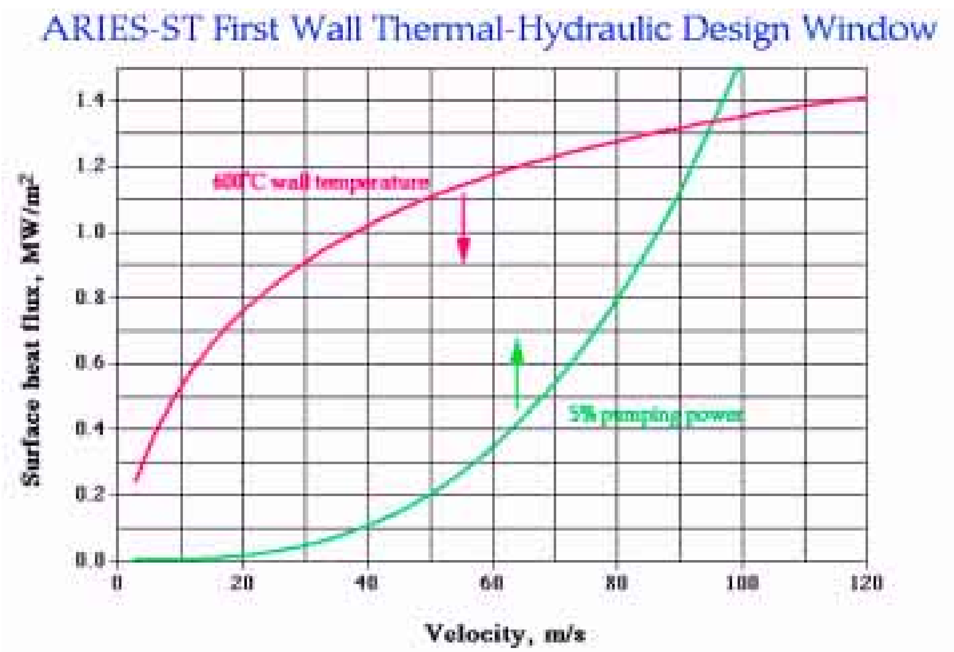
Major Parameters of ARIES-ST

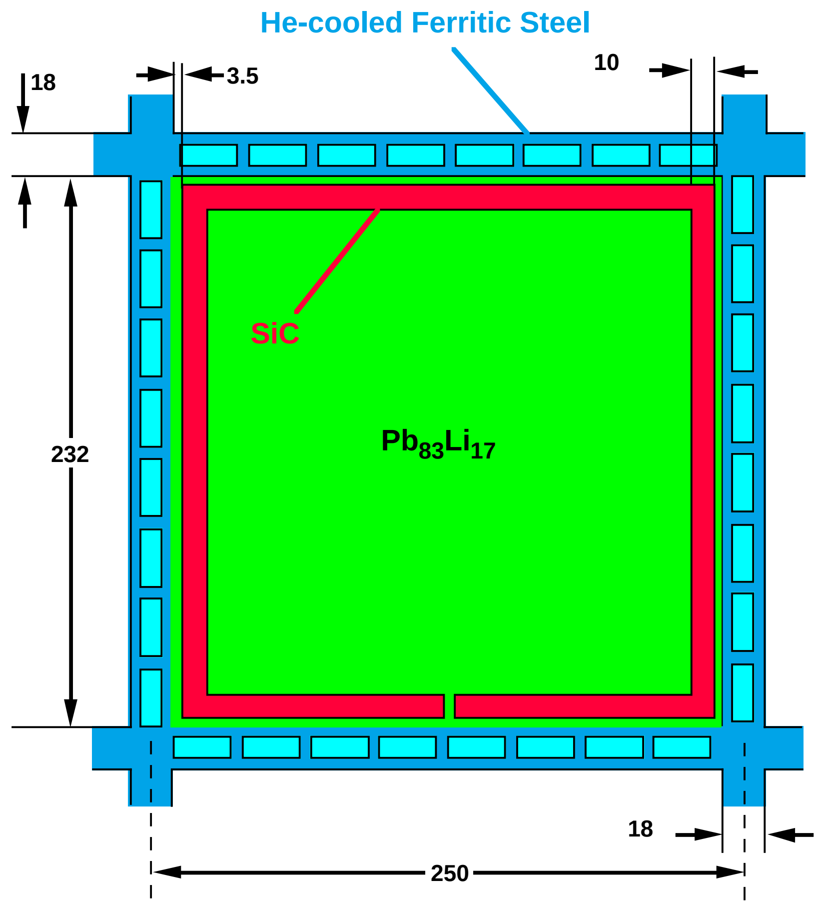
Aspect ratio	1.6
Major radius	3.2 m
Minor radius	2 m
Plasma elongation, κ_x	3.75
Plasma triangularity, δ_x	0.67
Plasma current	28 MA
Toroidal β	50%
Toroidal field on axis	2.1 T
Avg. neutron wall load	4.1 MW/m^2
Fusion power	2980 MW
Recirculating power	520 MW
TF Joule losses	325 MW
Net electric output	1000 MW



ARIES-ST Utilizes a Dual Coolant Approach to Uncouple Structure Temperature from Main Coolant Temperature

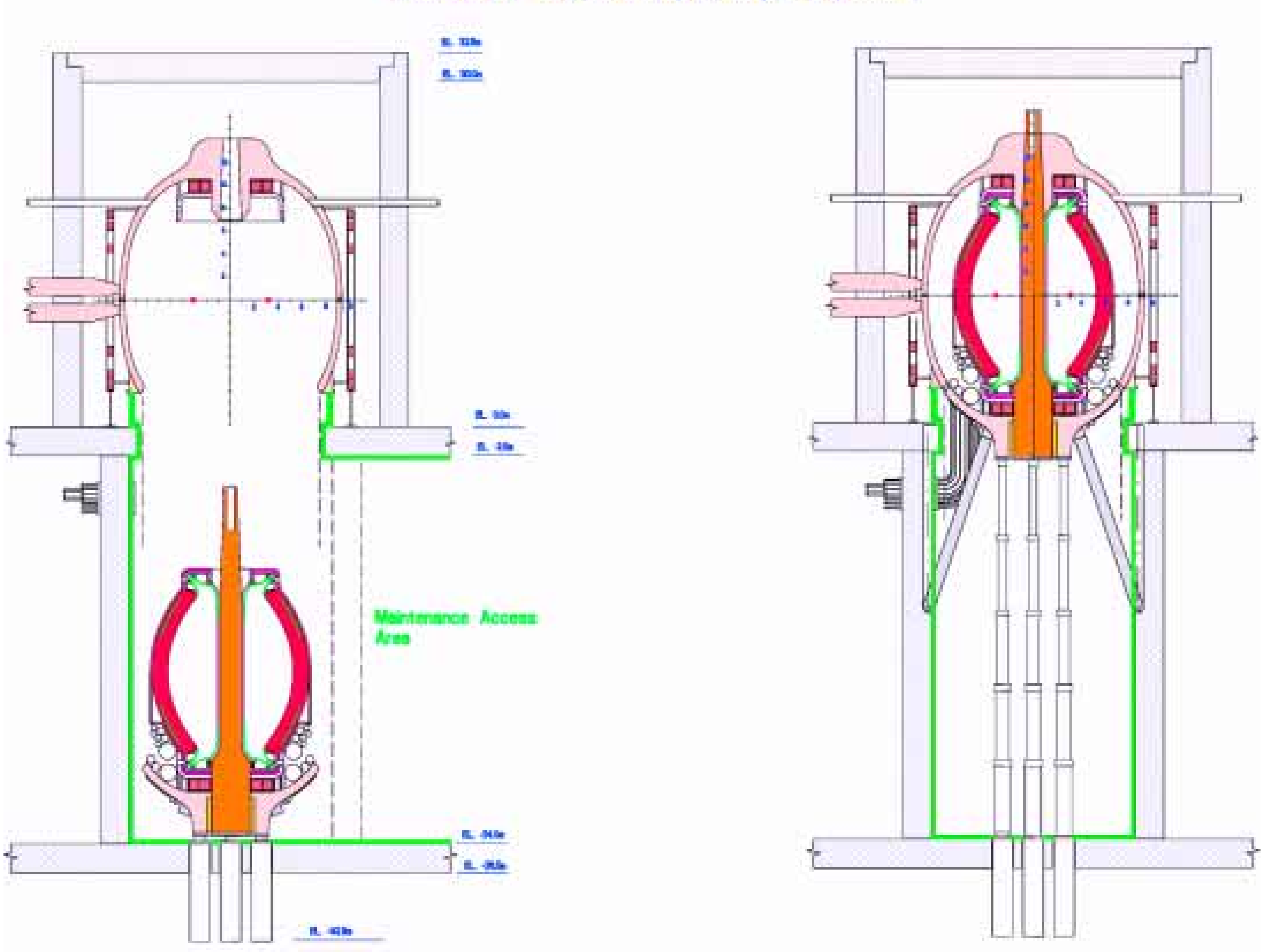
- ARIES-ST: Ferritic steel+Pb-17Li+He
- Flow lower temperature He (350-500°C) to cool structure and higher temperature Pb-17Li (480-800°C) for flow through blanket





Spherical Torus Geometry Offers Some Unique Design Features (e.g., Single-Piece Maintenance)

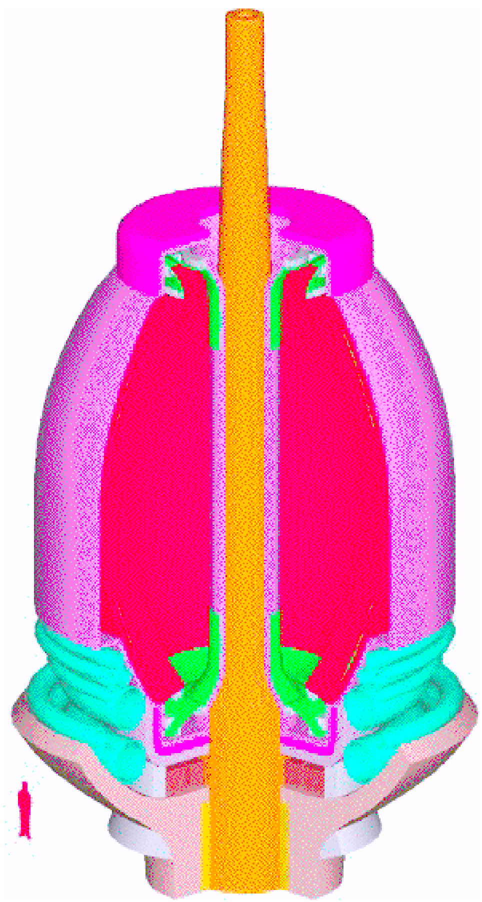
ARIES-ST Machine Addembly Sequence



(4)

(5)

Inboard shield on a spherical torus



ARIES-ST power core replacement unit

Previous perception: Any inboard (centerpost) shielding will lead to higher Joule losses and larger/more expensive ST power plants.

Conclusions of ARIES study: A thin (20 cm) shield actually improves the system performance .

– Reduces nuclear heating in the centerpost and allows for a higher conductor packing fraction
– Reduces the increase in electrical resistivity due to neutron-induced transmutation
– Improves the power balance by recovering high-grade heat from the shield
– Allows the centerpost to meet the low-level waste disposal requirement with a lifetime similar to the first wall (more frequent replacement of the centerpost is not required).

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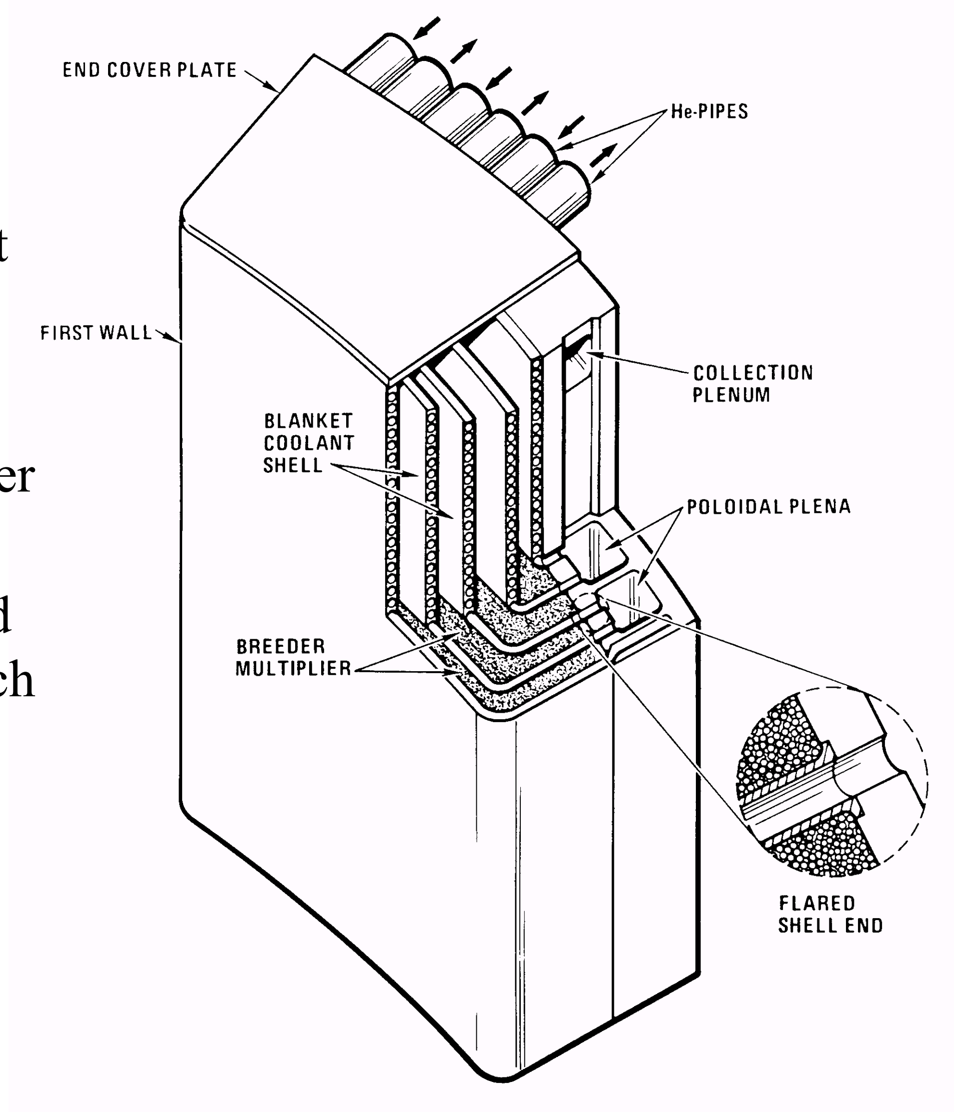
Impact of latest developments in many scientific disciplines are continuously considered, and play an important role in the attractiveness of fusion

Examples:

- SiC_f/SiC composite materials
- High-temperature Brayton power conversion cycles
- Advanced manufacturing techniques
- High-T_c superconductors
- Reliability, availability and maintainability

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

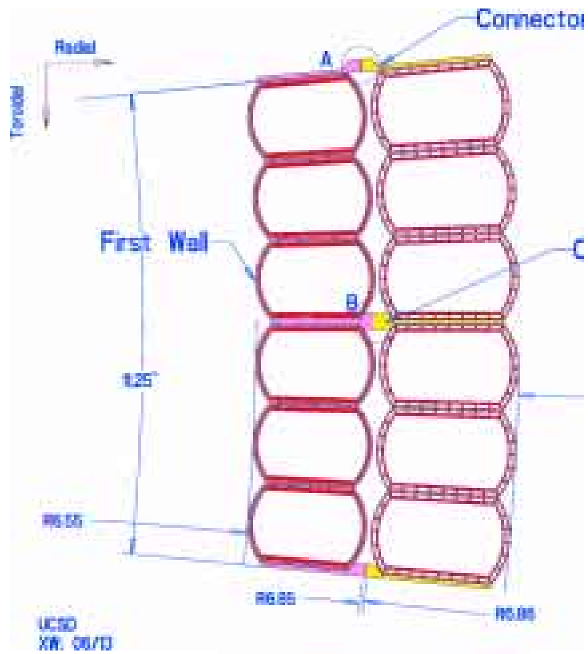
- Excellent safety & environmental characteristics (very low activation and very low afterheat).
- High performance due to high strength at high temperatures (>1000°C).
- Large world-wide program in SiC:
  - New SiC composite fibers with proper stoichiometry and small O content.
  - New manufacturing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

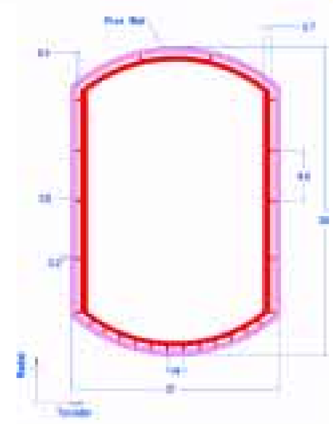


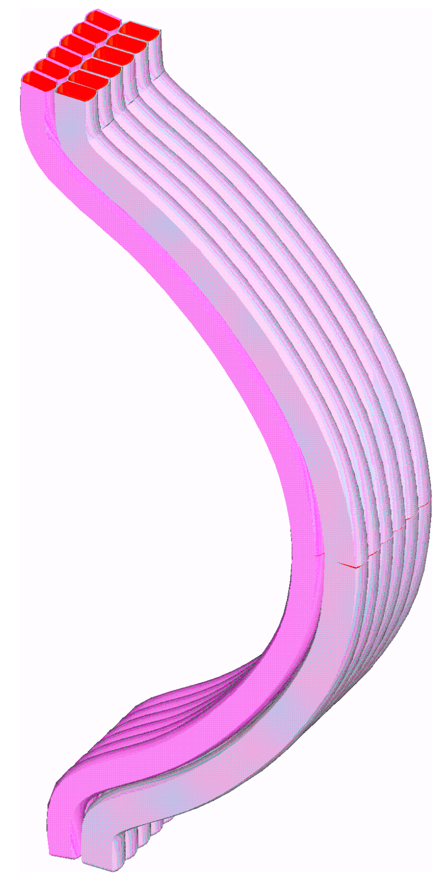
ARIES-AT^2: SiC Composite Blankets

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1100°C) while keeping SiC structure temperature below 1000°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

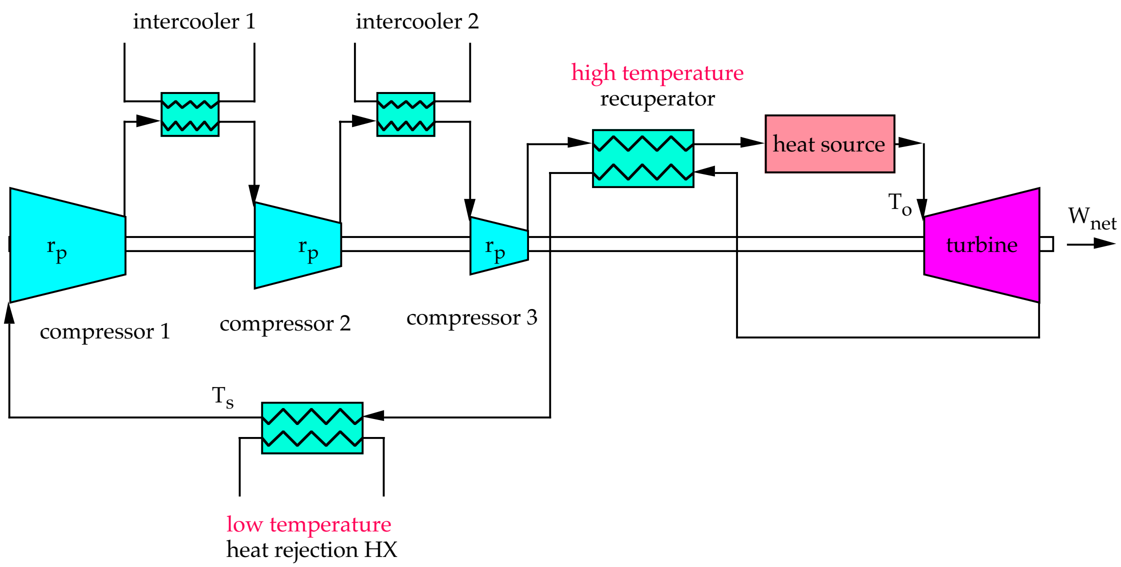


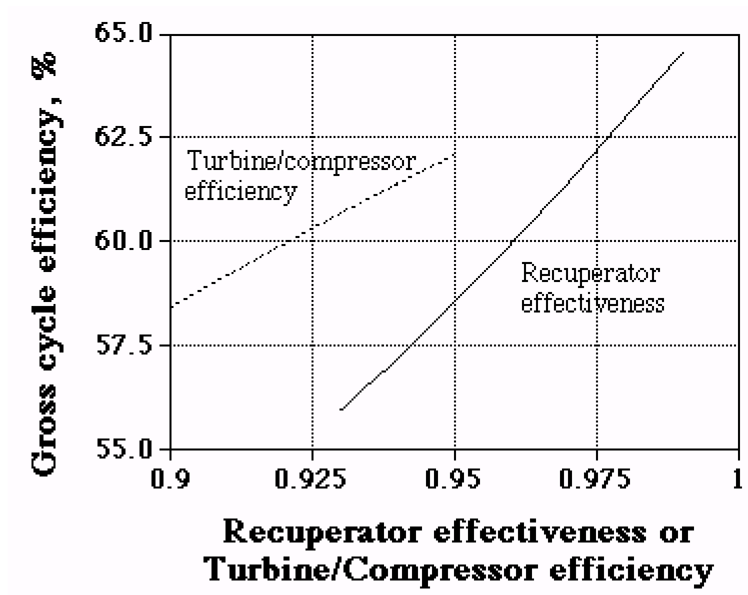




Recent Advances in Brayton Cycle Lead to Power Cycles With High Efficiency

- Conventional steam cycle — 35% — steel/water
- Supercritical steam Rankine — 45% — Li/V
- Low-temperature Brayton — >45% — advanced FS/PbLi/He
- High-temperature Brayton — 60% — SiC/He

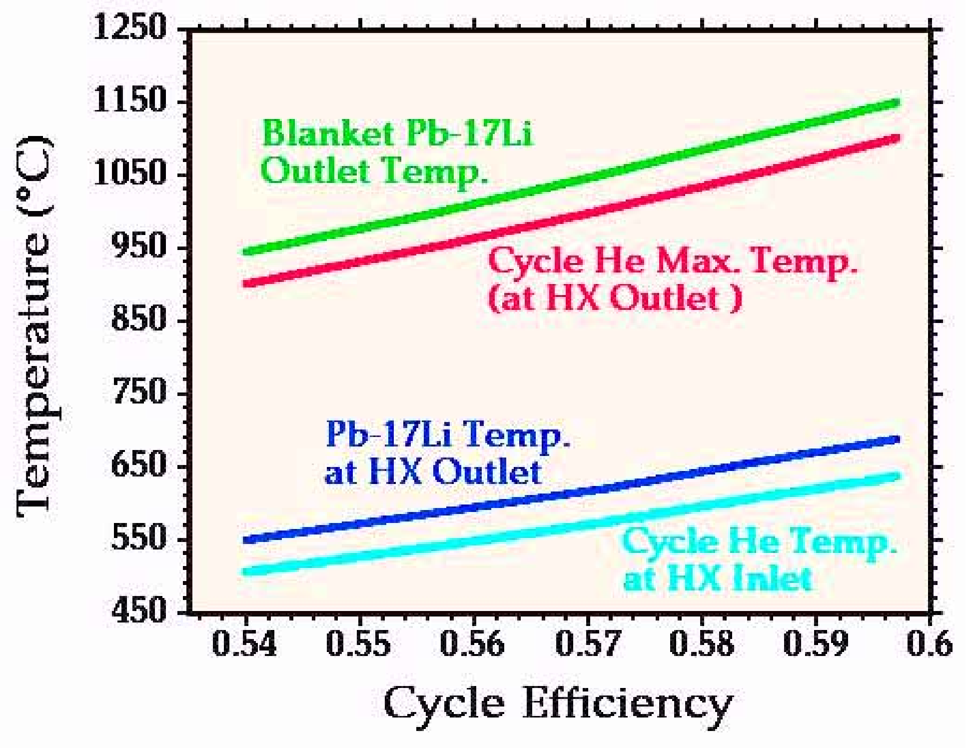




➢ A key improvement is the development of cheap, high-efficiency recuperators.

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
  - $(mCp)_{He}/(mCp)_{Pb\text{-}17Li} = 1$

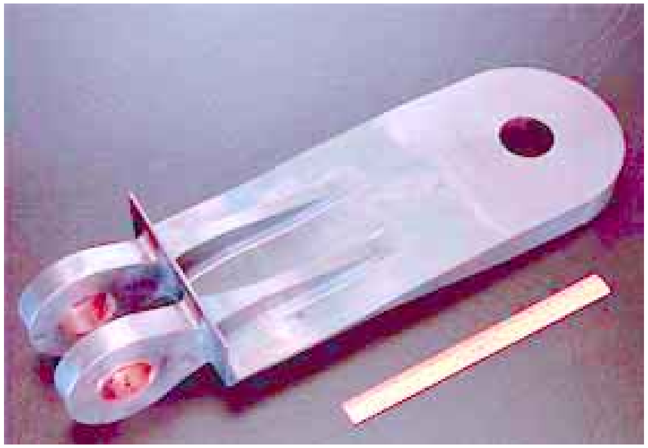


* R. Schleicher, A. R. Raffray, C. P. Wong, "An Assessment of the Brayton Cycle for High Performance Power Plant," 14th ANS Topical Meeting on Technology of Fusion Energy, October 15-19, 2000, Park City Utah

Revolutionary Fabrication Techniques May Significantly Reduce Fusion Power Core Costs

- **Fabrication of titanium components is being considered for Boeing aircraft to reduce airframe material and fabrication costs.**
- **Properties are equivalent to cast or wrought**
- **Process is highly-automated (reduced labor)**
- **In addition to titanium; SS316, H13 tool steel, IN625, and W have been formed (Cu is possible)**
- **Process can produce parts with layered or graded materials to meet functional needs**

AeroMet has produced a variety of titanium parts. Some are in as-built condition and others machined to final shape.

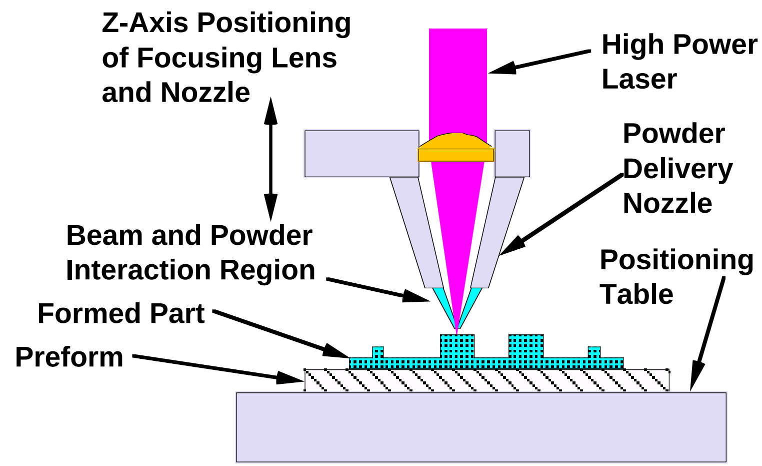


The machined laser-formed part shown at left is a fracture critical component which has successfully passed both fatigue and static strength tests originally designed for the forged components which it will be replacing. It is approximately 36” (900 mm) by 12” (300 mm) by 6” (150 mm). This component was fabricated for The Boeing Company under funding from the Office of Naval Research.

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
- Like stereo-lithography, construction of overhanging elements should be avoided – tapers up to 60° are possible

Schematic of Laser Forming Process



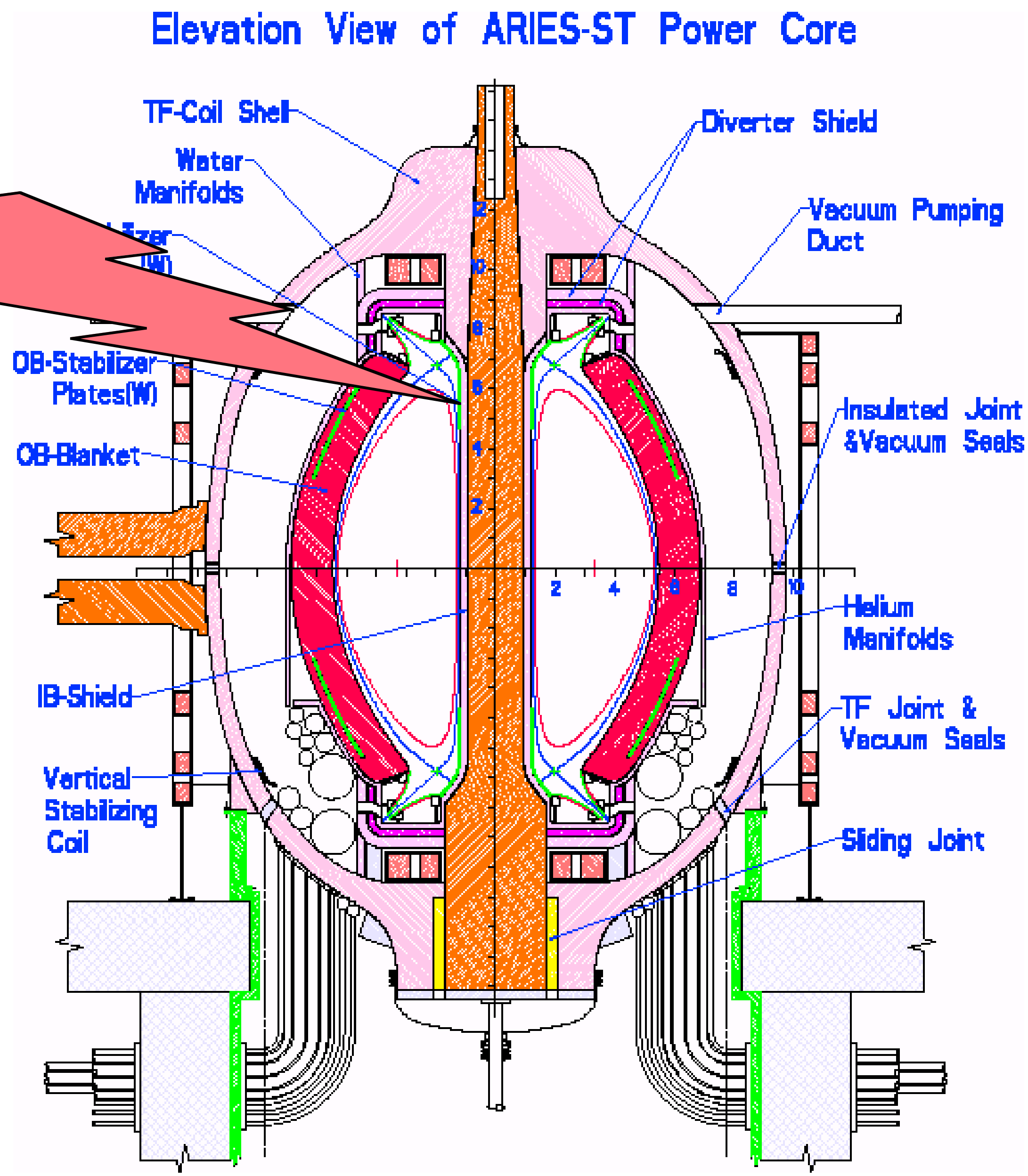
- Quantity of material constructed is limited only by the power of the lasers and the number of laser heads used
- Surface finish of the parts is typically 32 to 64 μ in. and can be as good as 10 μ in.

An Example

Problem Statement

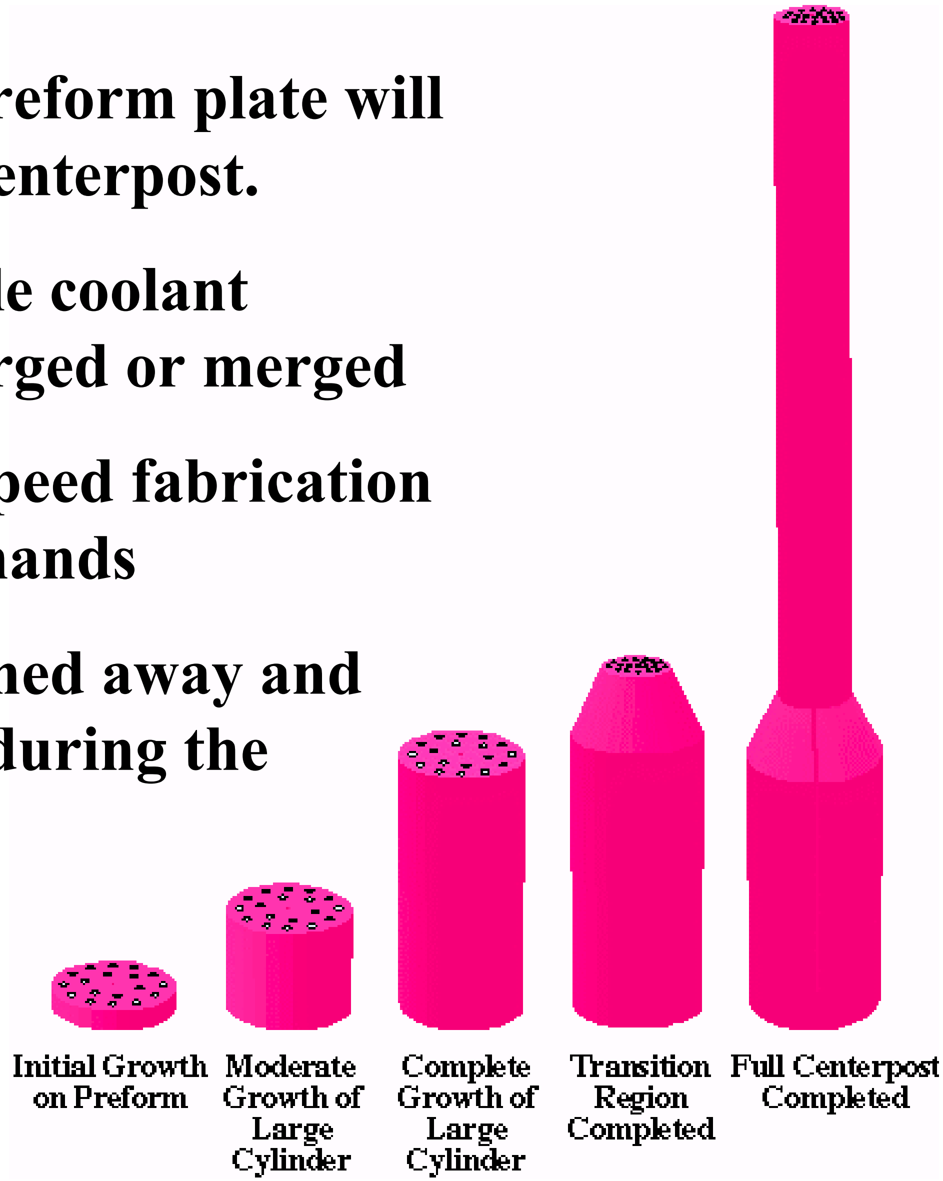
The Spherical Tokamak's copper center post was too expensive.

- 30 m long, 850 tonnes
- Water cooled
- Leak tight construction
- Complicated fabrication
- Conventional Cost ~ $68M, ($80/kg) replaced every six years
- Probably the most expensive component in the power core and certainly the highest annual cost item



Fabrication of ARIES-ST Centerposts Using Laser Forming was Assessed

- **An initial blank or preform plate will be used to start the centerpost.**
- **Complex and multiple coolant channels can be enlarged or merged**
- **Multiple heads can speed fabrication to meet schedule demands**
- **Errors can be machined away and new material added during the fabrication**



Costs Can Be Significantly Reduced

• Mass of centerpost with holes plus 5% wastage	894,000 kg
• Deposition rate with 10 multiple heads	200 kg/h
Total labor hours	8628 h
• Labor cost @ $150/h (with overtime and site premium)	$1,294,000
• Material cost, $2.86/kg (bulk copper alloy power cost)	$2,556,000
• Energy cost (20% efficiency) for elapsed time + 30% rework	$93,000
• Material handling and storage	$75,000
• Positioning systems	$435,000
• Melting and forming heads and power supplies	$600,000
• Inert atmosphere system	$44,000
• Process computer system	$25,000
Subtotal cost of centerpost	$5,122,000
• Contingency (20%)	$1,024,000
• Prime Contractor Fee (12%)	$738,000
Total centerpost cost	$6,884,000
• Unit cost (finished mass = 851,000 kg)	$8.09/kg

Highly Automated Fabrication

< 3 x Matl Cost

Compare to $80/kg with conventional fabrication ($68M)

High-Temperature Superconductors were Assessed for ARIES-AT

- Physics Implications:
  - Operation at higher fields (limited by magnet structures, wall loading)
  - Smaller size, plasma current and current drive requirements.
- Engineering Implications:
  - Operation at higher temperatures simplifies cryogenics (specially is operation at liquid nitrogen temperature is possible)
  - Decreased sensitivity to nuclear heating of cryogenic environment.

High-Temperature Superconductor Types

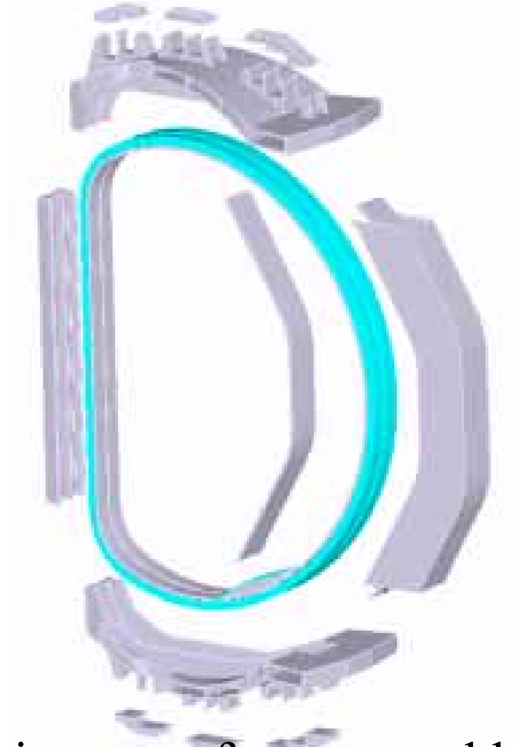
- YBCO
  - Highly textured tapes. Short tapes have been produced
  - High current density even at liquid nitrogen temperature as long as B is parallel to the surface of the tape.
- BSSCO (2212-2223 varieties)
  - Wires and tapes have been manufactures (100's m)
  - Easier to manufacture than YBCO but less impressive performance.
  - Much higher current density and critical field compared to Nb_3Sn at 4.2K

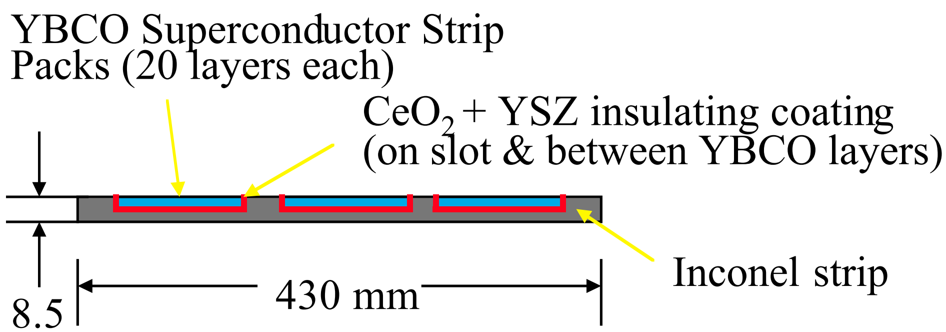
Use of High-Temperature Superconductors Simplifies the Magnet Systems

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

- HTS does offer <u>operational</u> advantages:
  - Higher temperature operation (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





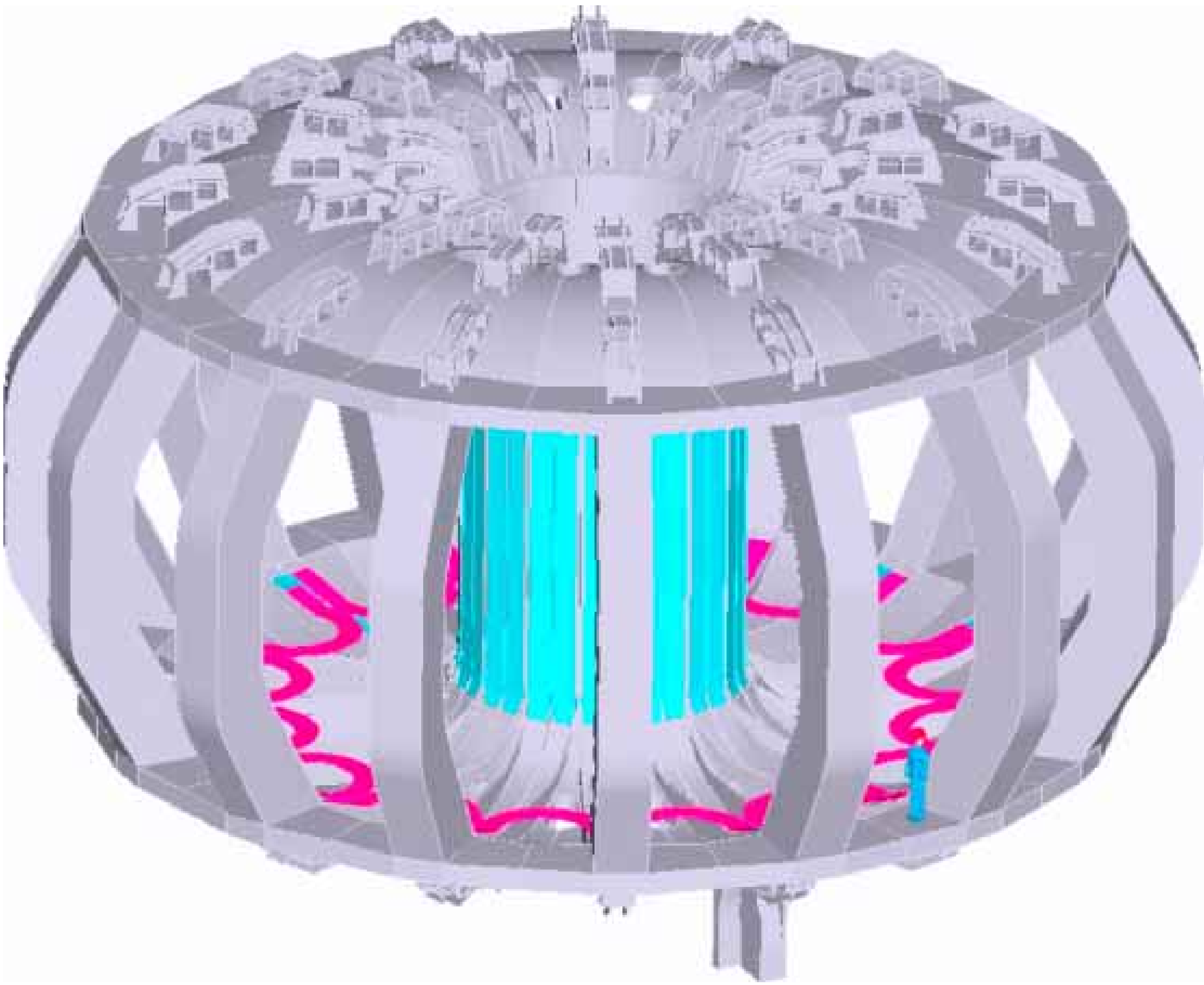
- Inexpensive manufacture would consist of layering HTS on structural shells with minimal winding!
  - If HTS at $1000/kg, and cost of structure is $40/kg, then cost of magnet could be ~$50/kg
  - Presently, HTS costs >10 x LTS.

RAMI: Reliability, Availability, Maintainability and Inspectability

- A = MTBF/(MTBF+MTTR)
- Maintainability: Full sector maintenance has been shown to offer the best hope of short down time
  - Modular power core sector replacement
  - Simple coolant and mechanical connections
  - Highly automated maintenance operations
  - Building designed for remote maintenance
  - Sectors can be repaired off-line
  - Better inspection also means higher reliability
- Reliability: No data base, but low failure rate should be possible through
  - Simple design and fabrication
  - Wide operating margins (T, p, s)
  - Failure tolerance & redundancy

*** MTTR = Mean Time To Repair, MTBF = Mean Time Between Failure**

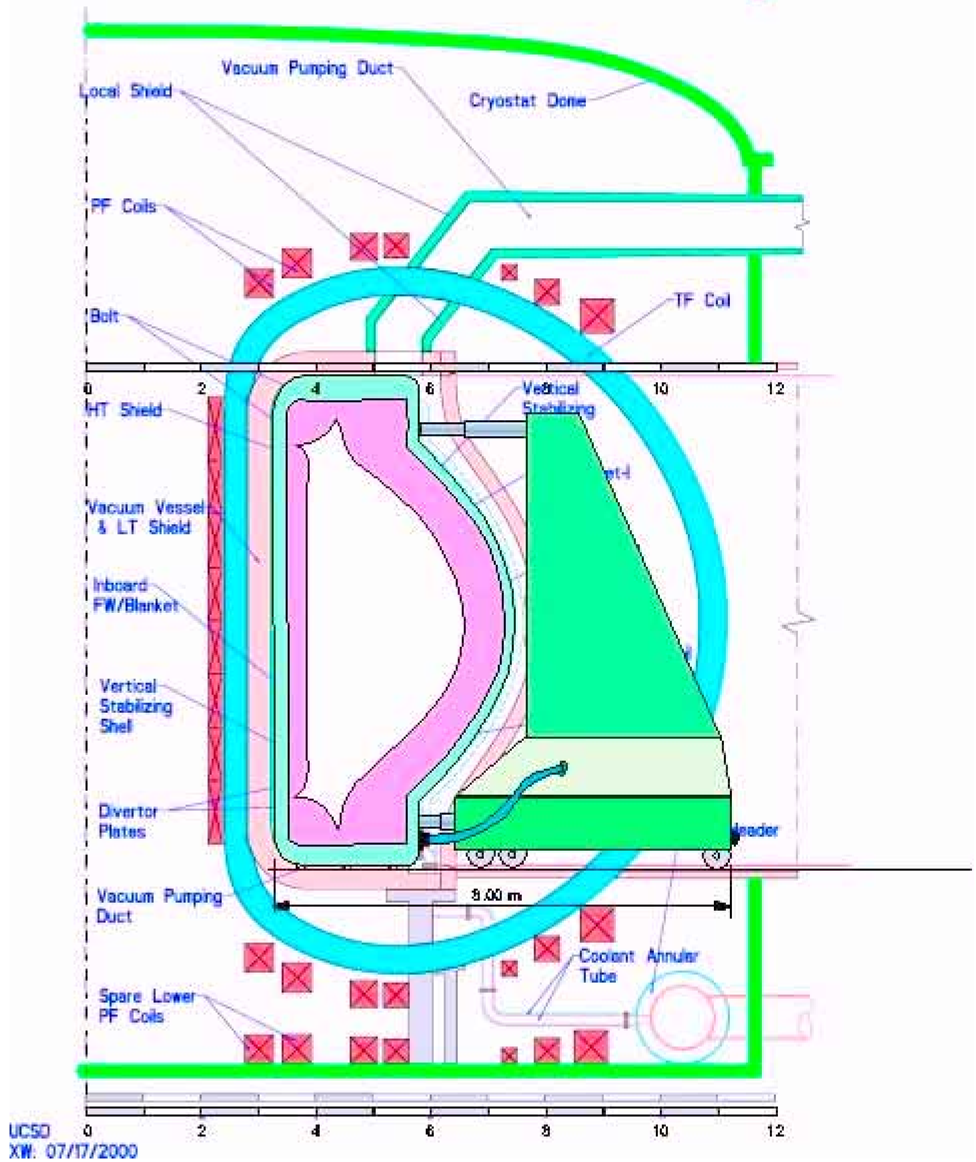
ARIES-AT Toroidal-Field Magnets



Sector Removal

Remote equipment is designed to remove shields and port doors, enter port enclosure, disconnect all coolant and mechanical connections, connect auxiliary cooling, and remove power core sector

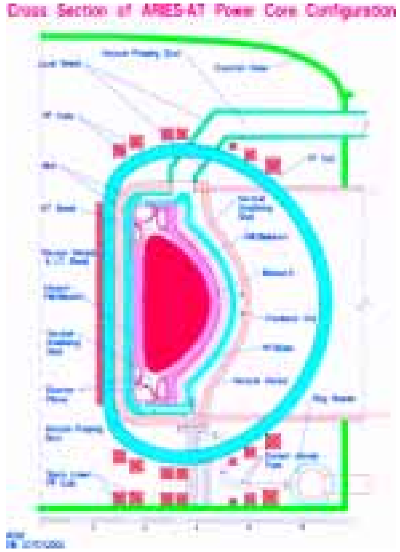
Cross Section of ARIES-AT Power Core Configuration



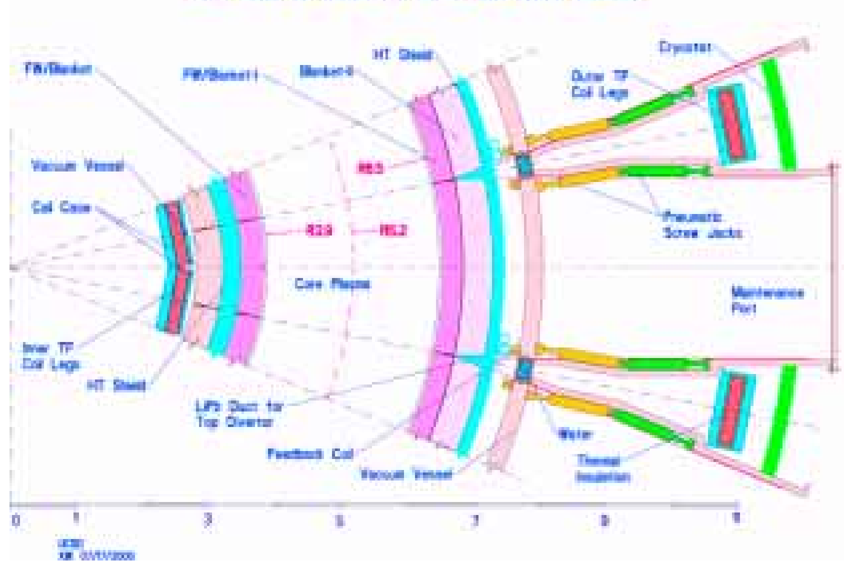
ARIES-AT Sector Replacement

Basic Operational Configuration

Cross Section of ARIES-AT Power Core Configuration

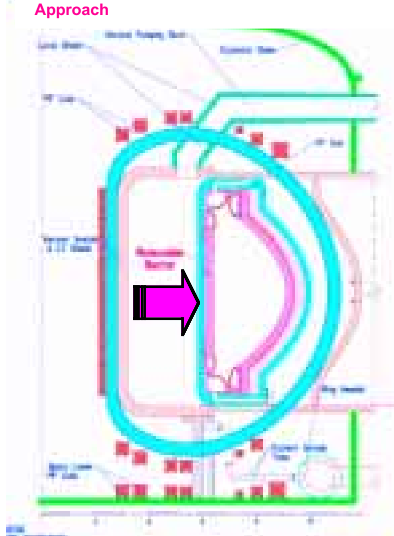


Plan View of ARIES-AT Power Core(1/16 Sector)

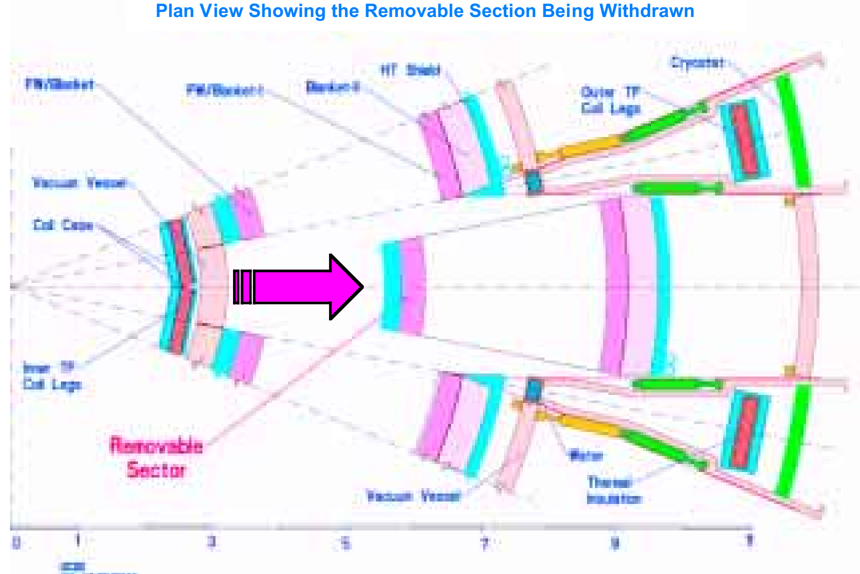


Withdrawal of Power Core Sector with Limited Life Components

Cross Section Showing Maintenance Approach

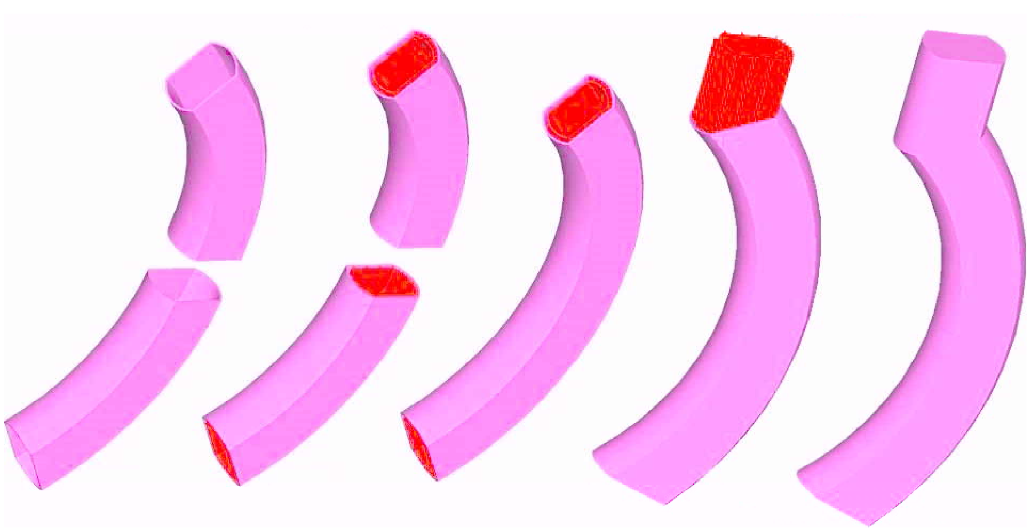


Plan View Showing the Removable Section Being Withdrawn



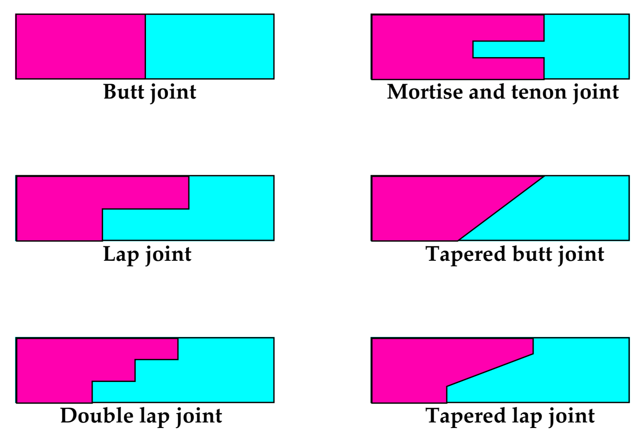
Reliability can be achieved through sound design principles and testing

- Perception of poor availability is based on water-cooled steel, ceramic breeder blanket *(Bünde, Perkins, Abdou)*
  - 220 km of pipe
  - 37,000 butt welds
  - 5 km of longitudinal welds



ARIES-AT blanket construction is simple and robust

- Low failure rate is possible through:
  - Simple design and fabrication
  - Wide operating margins (T, p, σ)
  - Failure tolerance & redundancy
- ARIES-AT
  - 3680 m of pipe, 1440 braze joints
  - <1500 m braze length to headers (173 m exposed to plasma)

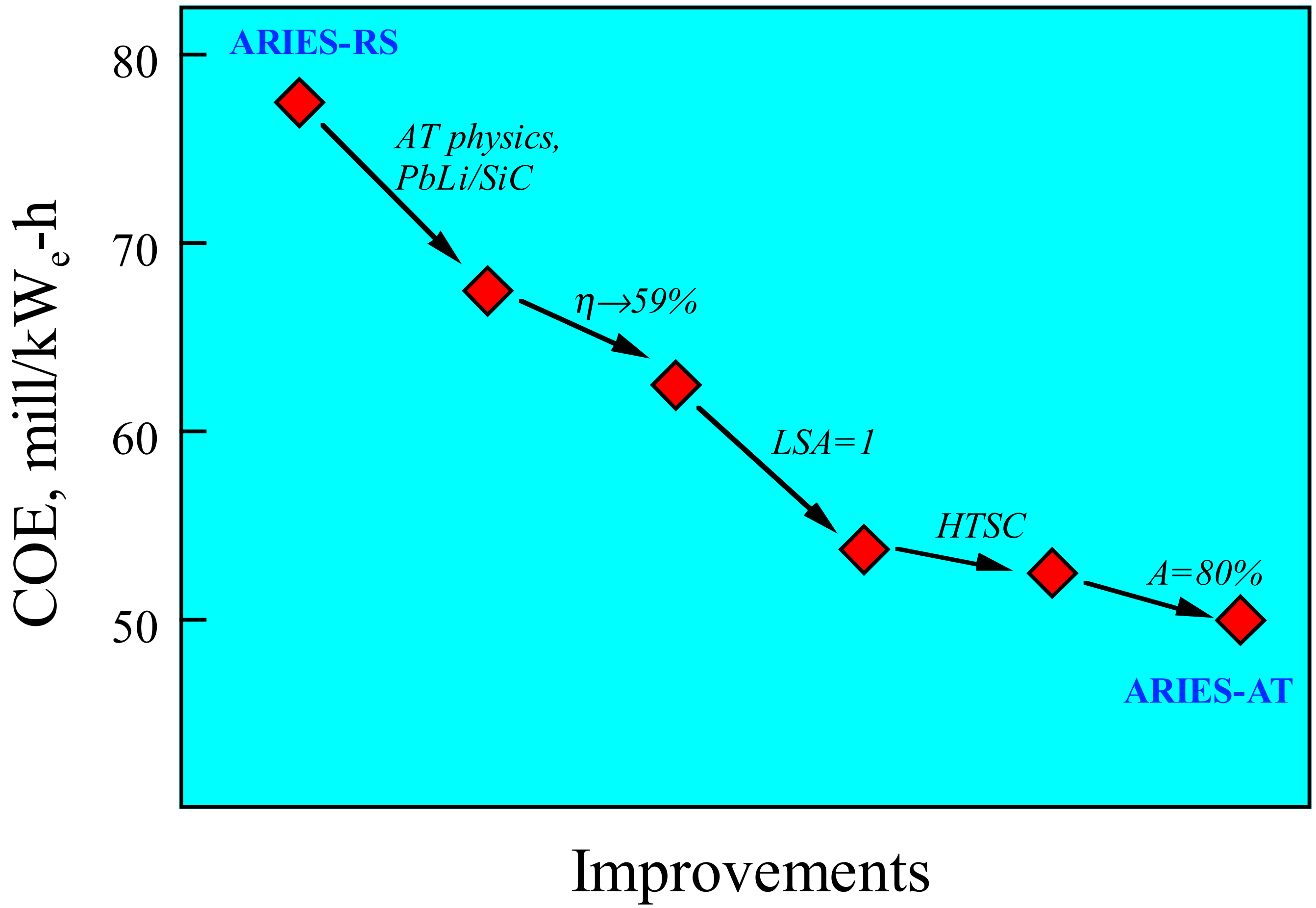


Outline

- Mission and organization
- Making the case for fusion
- Recent power plant studies
- Advances in physics and technology

➢ **Progress and prospects**

Individual advances on several fronts help improve the attractiveness of fusion

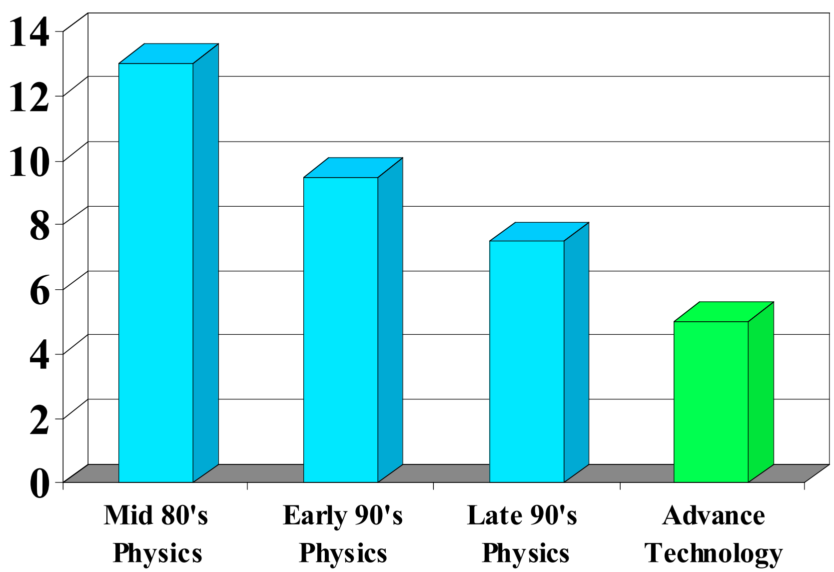


Our Vision of Tokamaks Has Improved Drastically in the Last Decade

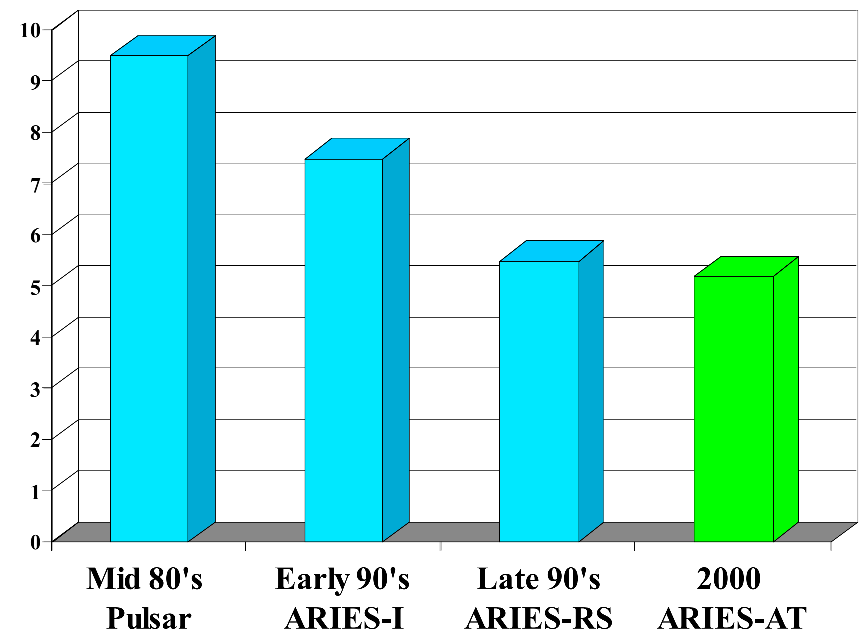
	80s physics	90s physics		
	Pulsar	ARIES-I	ARIES-RS	ARIES-AT
Major radius (m)	9	7	5.5	5.2
β	2.3%	1.9%	5%	9.2%
β_N	3	3.2	4.8	5.4
Plasma current (MA)	10	10 (68% bs)	11 (88% bs)	13 (91% bs)
COE (¢/kWh)	13	9.5	7.5	5

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 (¢/kWh)



Major radius (m)



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 ¢/kWh

Conclusions

- Customer requirements establish design requirements and attractive features for a competitive commercial product.
- Progress in the last decade is impressive and suggests that fusion can achieve its potential as a safe, clean, and economically attractive power source.
- Additional requirements for fusion research:
  - A reduced cost development path
  - Lower capital investment in plants.

For more information, visit our web site at aries.ucsd.edu