

Overview of the ARIES Program

Farrokh Najmabadi

University of California San Diego

Presentation to:

ARIES Program Peer Review

August 18, 2000

UC San Diego

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

ARIES Web Site: <http://aries.ucsd.edu/ARIES>

Advanced Design and Analysis Activities Help Guide Fusion Research

Breakdown of the Advanced Design Activities:

➤ NSO

➤ “System Studies”

- Concept exploration studies;
- Studies of markets, customers, and the role of fusion in a sustainable global energy strategy;
- National Fusion Power Plant Studies Program (ARIES).

ARIES Mission and Organization

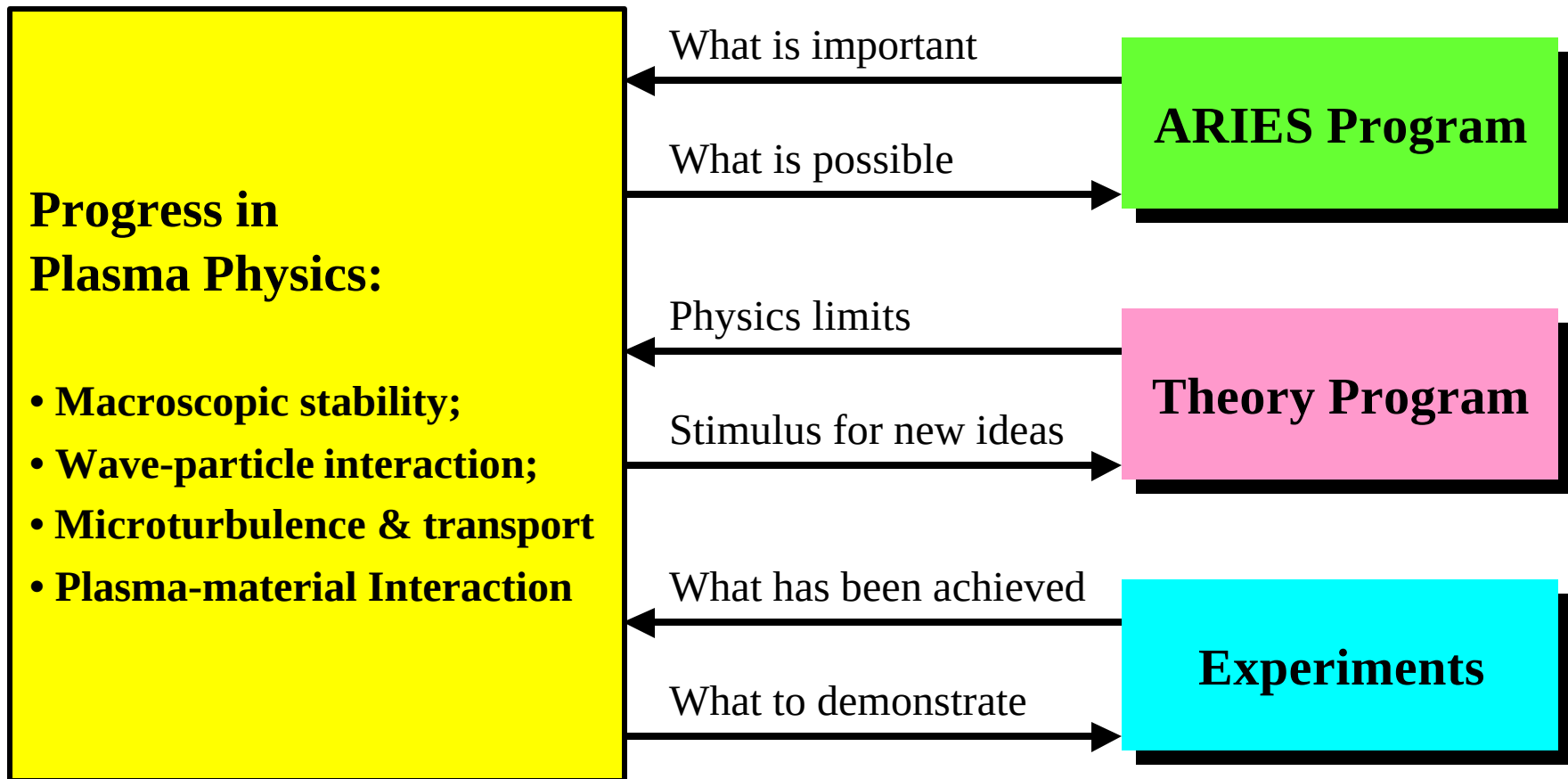
ARIES Research Bridges the Science and Energy Missions of the US Fusion Program

➤ 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.

- Commercial fusion energy is the most demanding of the program goals, and it provides the toughest standard to judge the usefulness of program elements.
- Science of fusion power plants involves subtle combinations of physics, technology, and engineering. Extensive systems studies are needed 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.

ARIES Program Identifies Key R&D Issues and Provides a Vision for the Program



- ✓ ARIES studies have influenced research priorities in each of these areas and have been guided by new experimental trends and theoretical concepts.

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

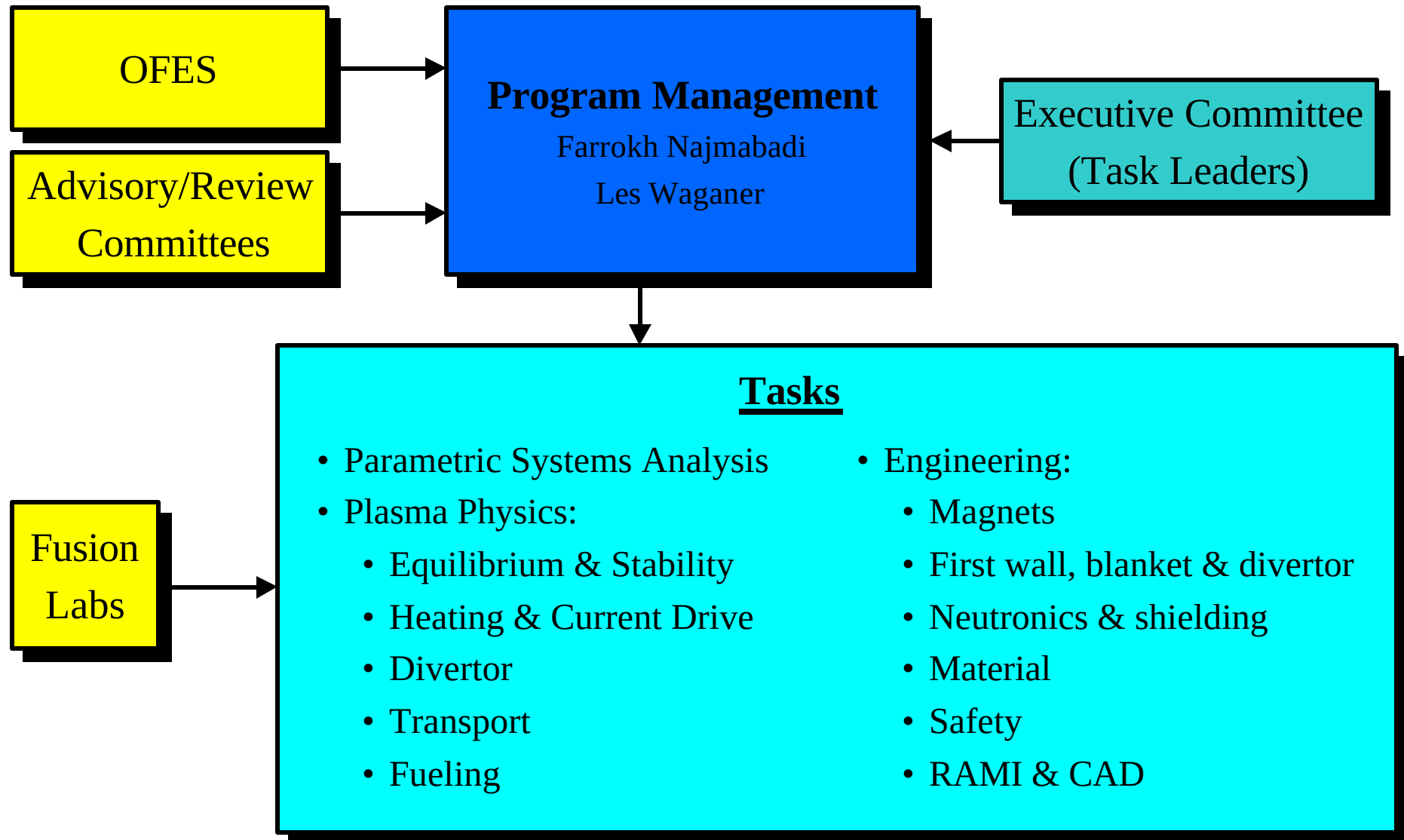
- TITAN reversed-field pinch (1988)
- ARIES-I first-stability tokamak (1990)
- ARIES-III D-³He-fueled tokamak (1991)
- ARIES-II and -IV second-stability tokamaks (1992)
- Pulsar pulsed-plasma tokamak (1993)
- SPPS stellarator (1994)
- Starlite study (1995) (goals & technical requirements for power plants & Demo)
- ARIES-RS reversed-shear tokamak (1996)
- ARIES-ST spherical torus (1999)
- Fusion neutron source study (2000)
- ARIES-AT advanced technology and advanced tokamak (2000)



National ARIES Program Allows Fusion Scientists to Investigate Fusion Systems Together

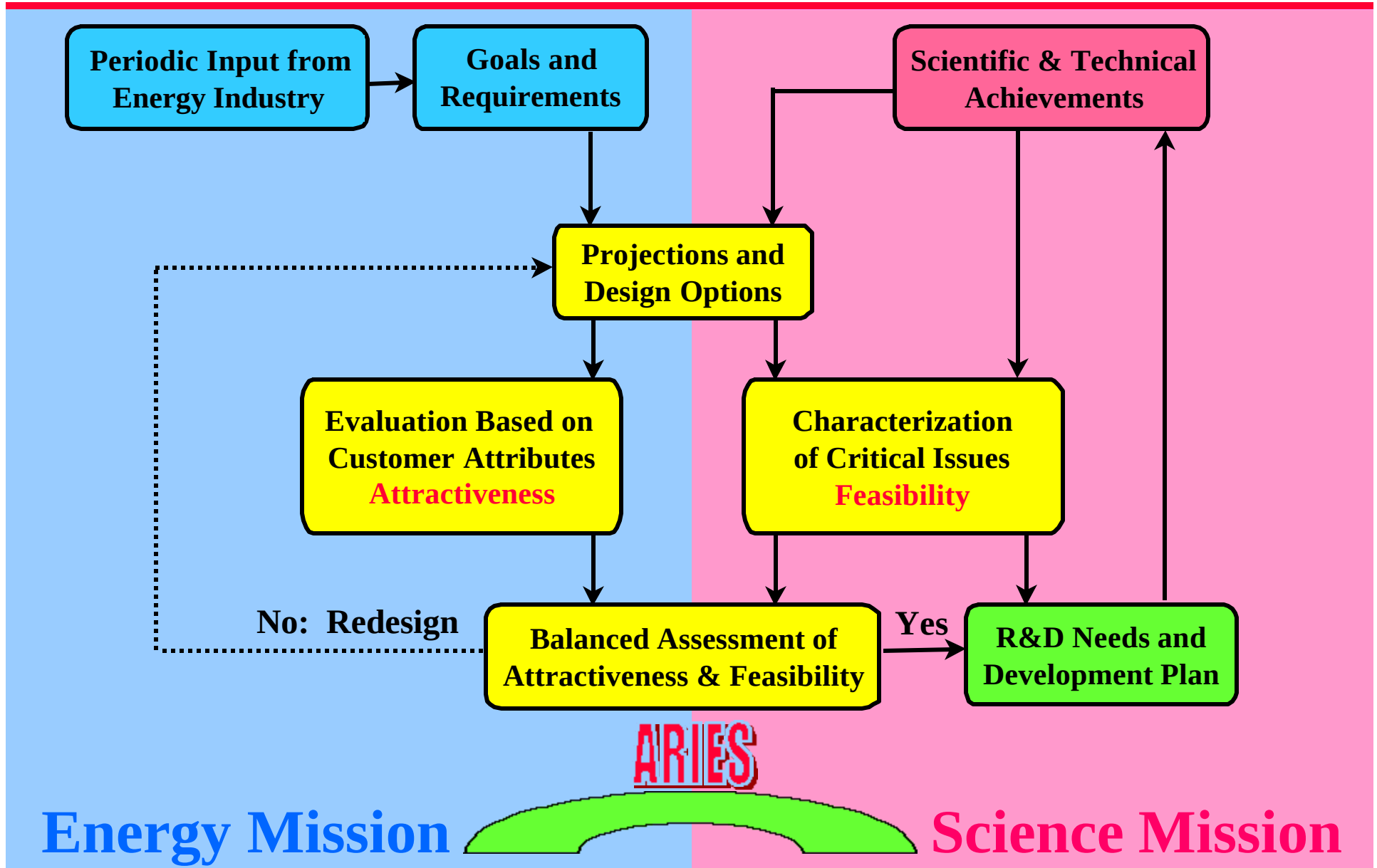
- The team comprises key members from major fusion centers (universities, national laboratories, and industry). A typical team member spends 25% of his time on this activity. About 2/3 of resources is allocated to universities this year. Seven students were supported last year.
- Decisions are made by consensus in order to obtain the best technical solution without institutional bias.
- Team is flexible and expert groups and advocates are brought in as needed to ensure the flow of the latest information from R&D program. As such, high-leverage issues are readily transferred back to the R&D program.
- Workshop and “Town meeting” are held for direct discussion and dissemination of the results.
- Because we draw from expertise of the national program, we are unique in the world in the ability to provide a fully integrated analysis of power plant options including plasma physics, fusion technology, economics, safety, etc.

Program is Organized as a Team



Technical Approach

ARIES Research Framework: Assessment Based on Attractiveness & Feasibility



Conceptual Design 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.

ARIES Program Performs Detailed Integrated Analysis of High-Leverage Systems

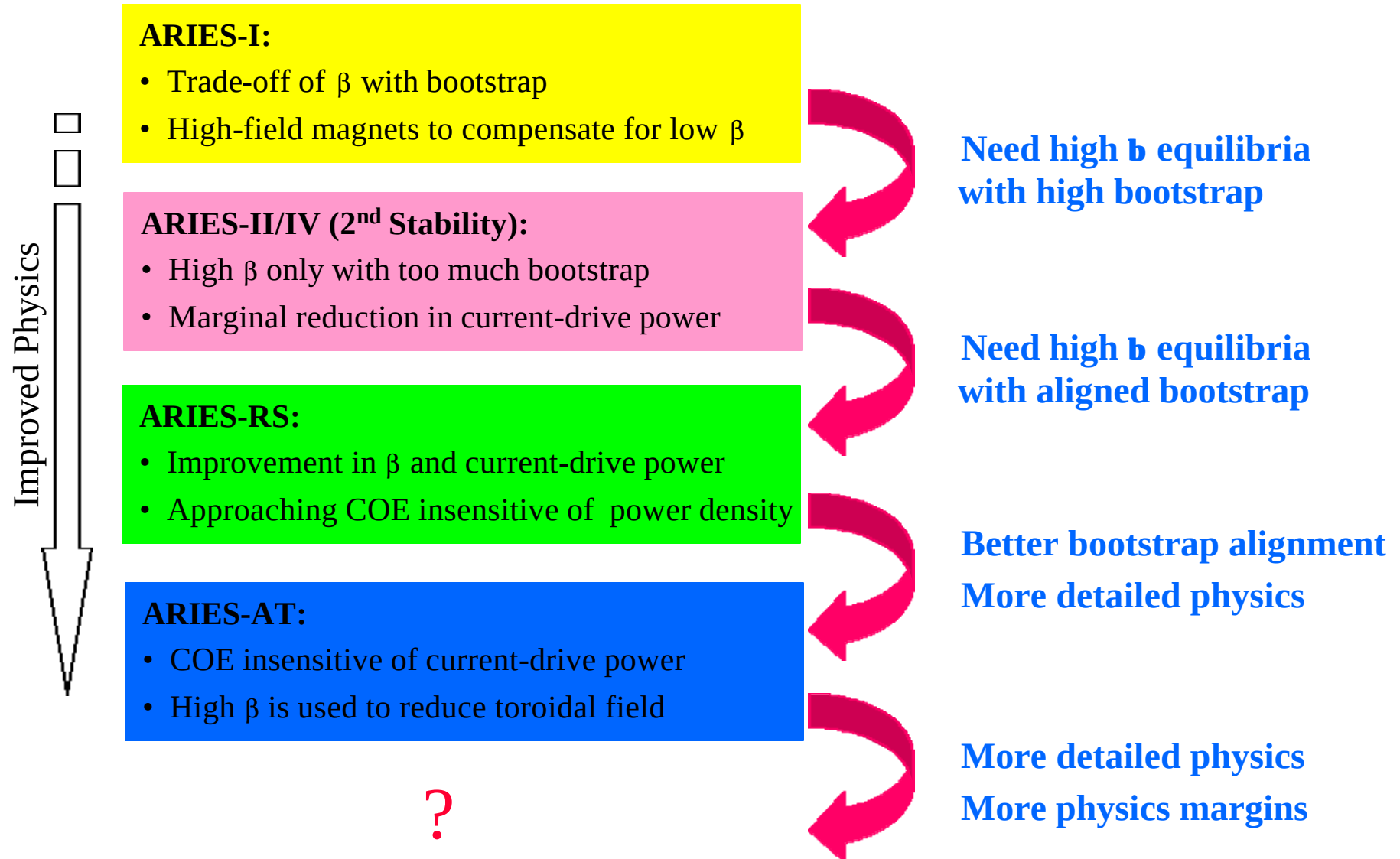
- Detailed and in-depth analysis is necessary to make scientific progress and impact the R&D program:
 - * Invoke physics and engineering constraints which are not in present-day experiments (e.g., simultaneous high power and high particle flux to divertor)
 - * Interaction and trade-off among plasma parameters (MHD β limit, heating & current-drive, divertor, transport);
 - * Interfaces between fusion plasma and other components (e.g., restriction on plasma elongation by location of stabilizer, and triangularity by inboard divertor slot)
- In many areas models and tools necessary to analyze fusion systems are developed.

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

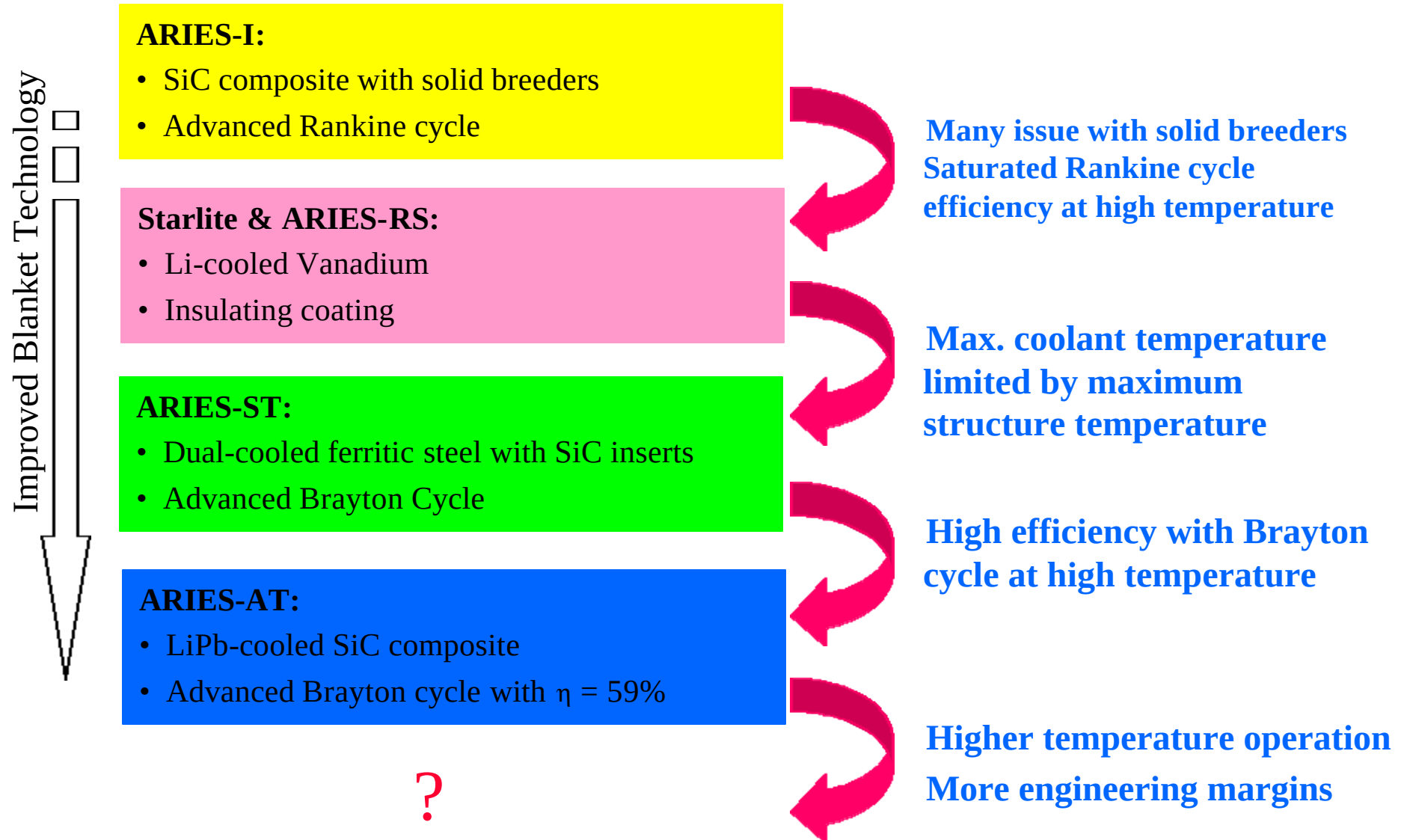
Requirements:

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

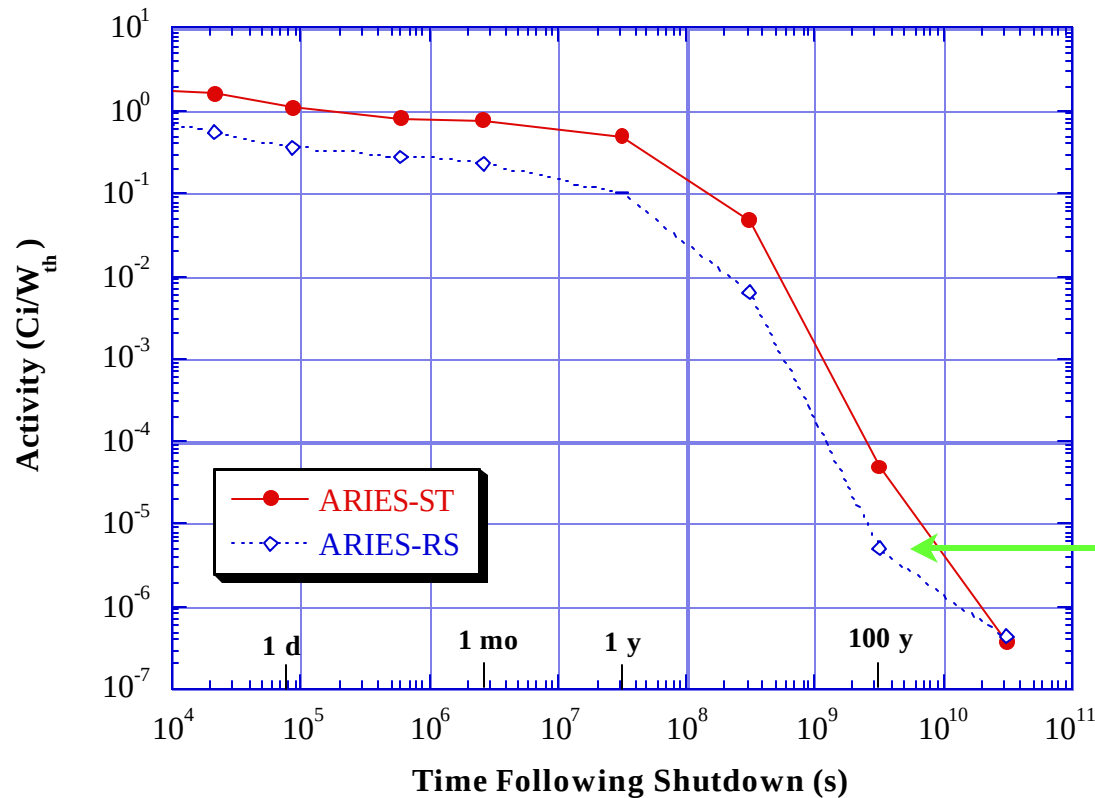
Continuity of ARIES research has led to the progressive refinement of research



Continuity of ARIES research has led to the progressive refinement of research



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



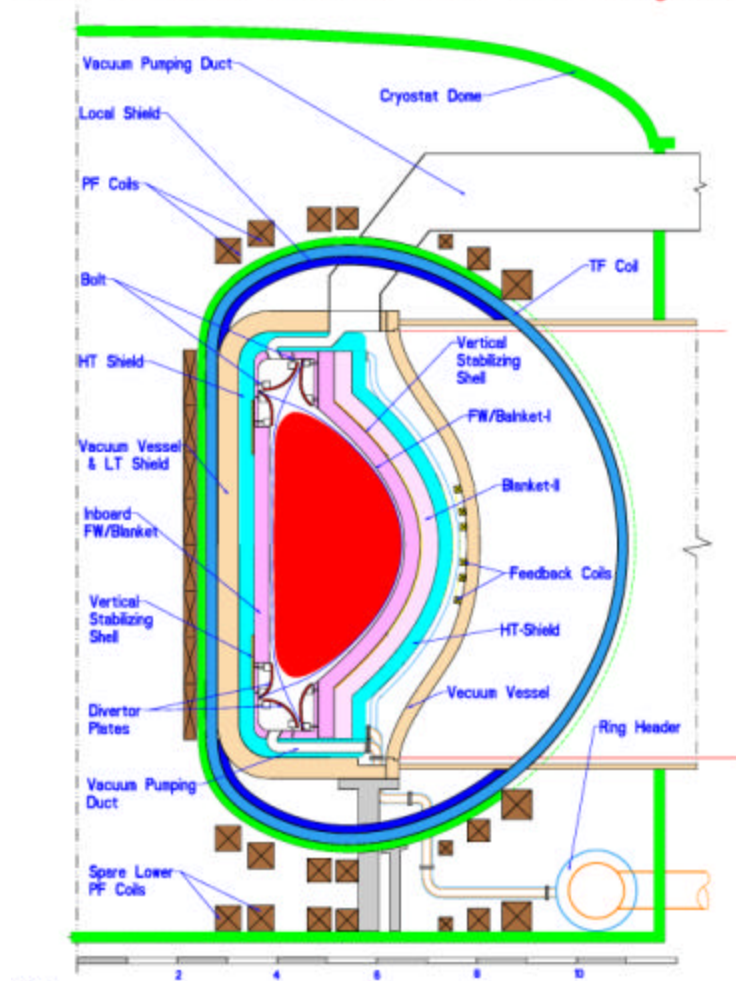
ARIES-RS: V Structure, Li Coolant;
ARIES-ST: Ferritic Steel Structure,
He coolant, LiPb Breeder;
Designs with SiC composites will
have even lower activation levels.

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

- **Low afterheat** results in excellent safety characteristics
- **Low specific activity** leads to low-level waste that decays away in a few hundreds years.

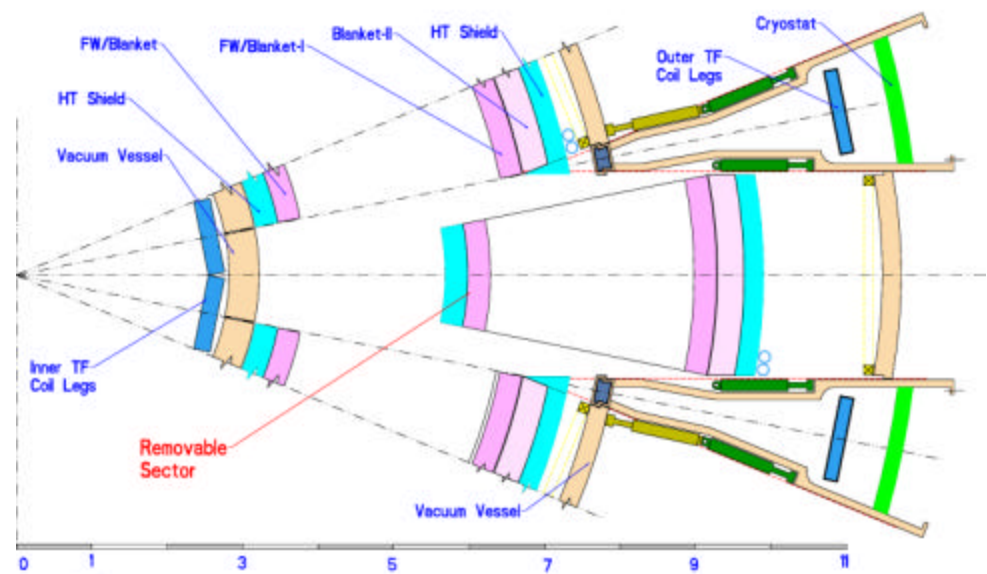
ARIES-AT Also Uses A Full-Sector Maintenance Scheme

Cross Section of ARIES-AT Power Core Configuration



UCSD
XN: 06/14/2000

Plan View of Showing the Removable Sector Being Withdrawn



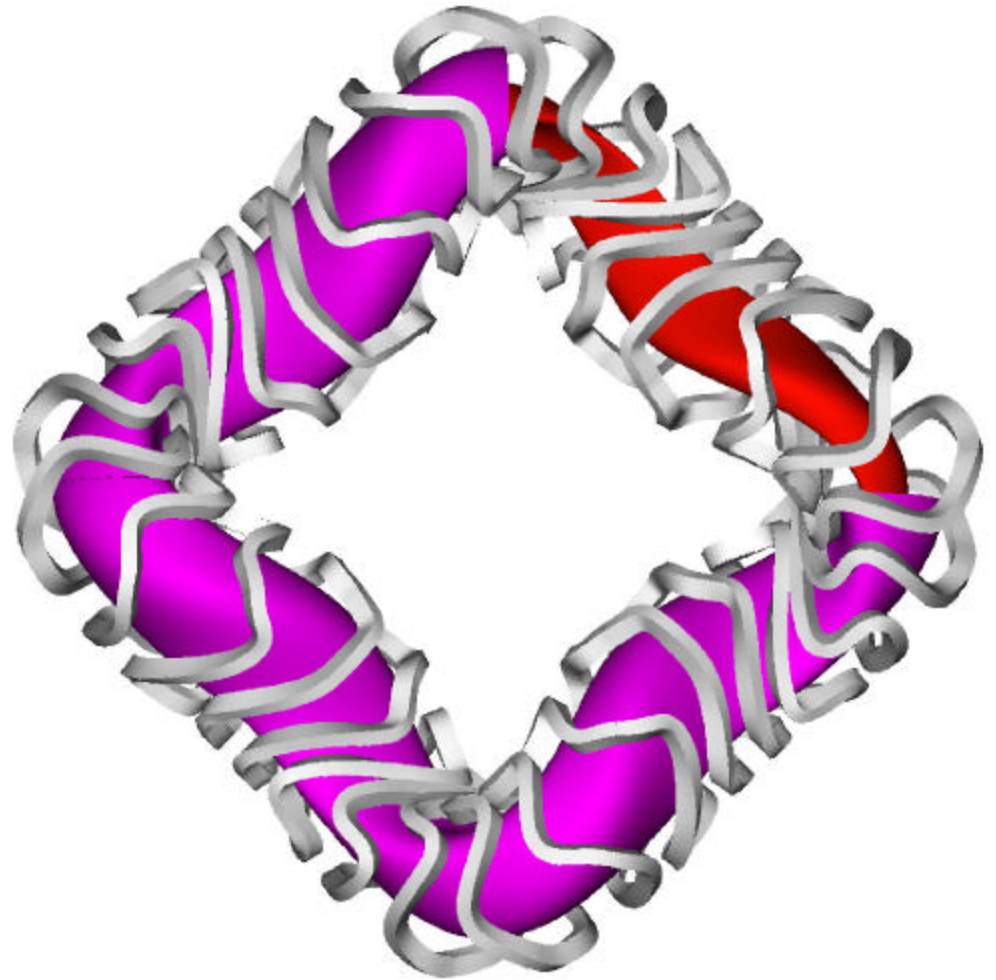
UCSD
XN: 06/15/2000

Visions for the Fusion Program

Stellarator Power Plant Study focused the US

Stellarator Activity on Compact Stellarators

- Modular MHH configuration represented a factor of two improvement on previous stellarator configuration with attractive features for power plants.
- Many critical physics and technology areas were identified.

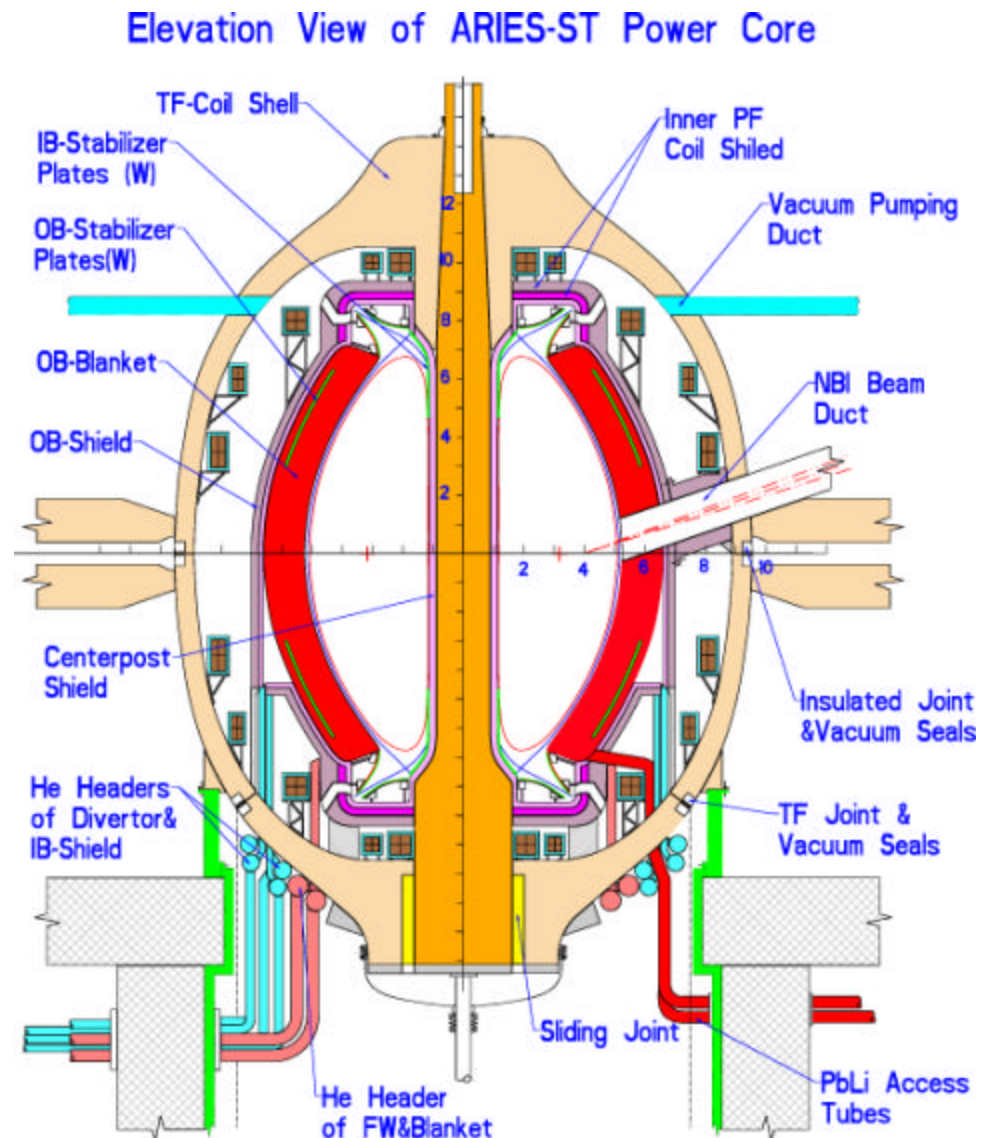


The ARIES-ST Study Has Identified Key Directions for Spherical Torus Research

- Substantial progress is made towards optimization of high-performance ST equilibria, providing guidance for physics research.

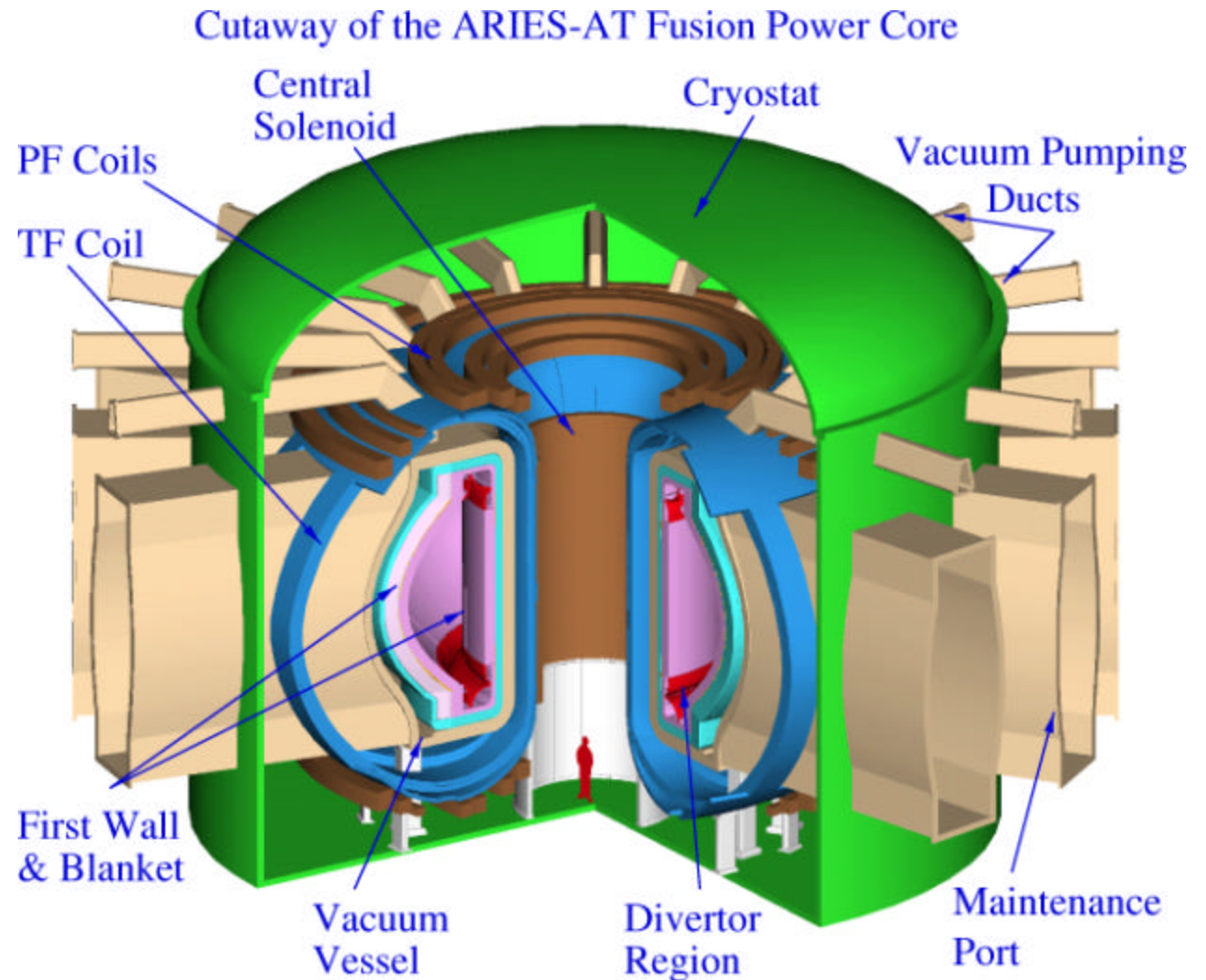
Assessment:

- 1000-MWe ST power plants are **comparable in size and cost** to advanced tokamak power plants.
- Spherical Torus geometry offers unique design features such as **single-piece maintenance**.
- Modest size machines can produce significant fusion power, leading to **low-cost development pathway** for fusion.



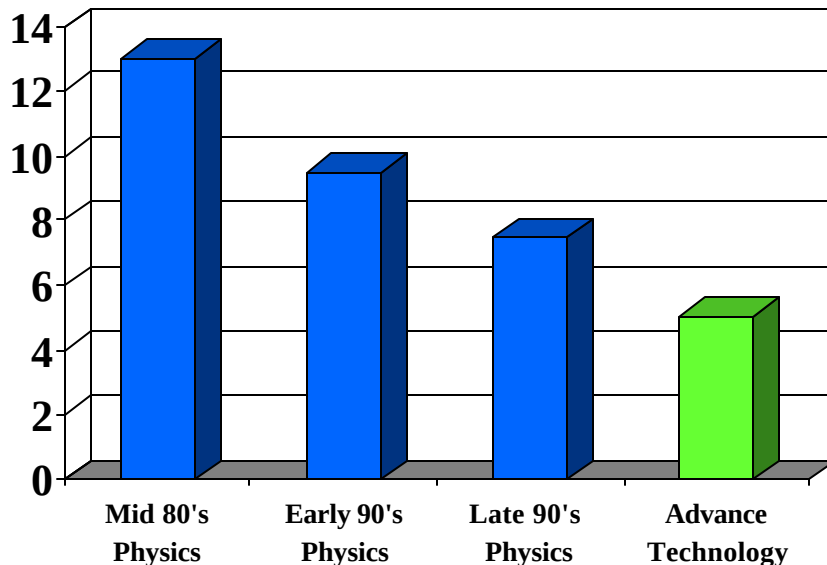
Combination of Advanced Tokamak modes and Advanced Technologies lead to an attractive vision for fusion – ARIES AT

- * Competitive cost of electricity;
- * Steady-state operation;
- * Low level waste;
- * Public & worker safety;
- * High availability.

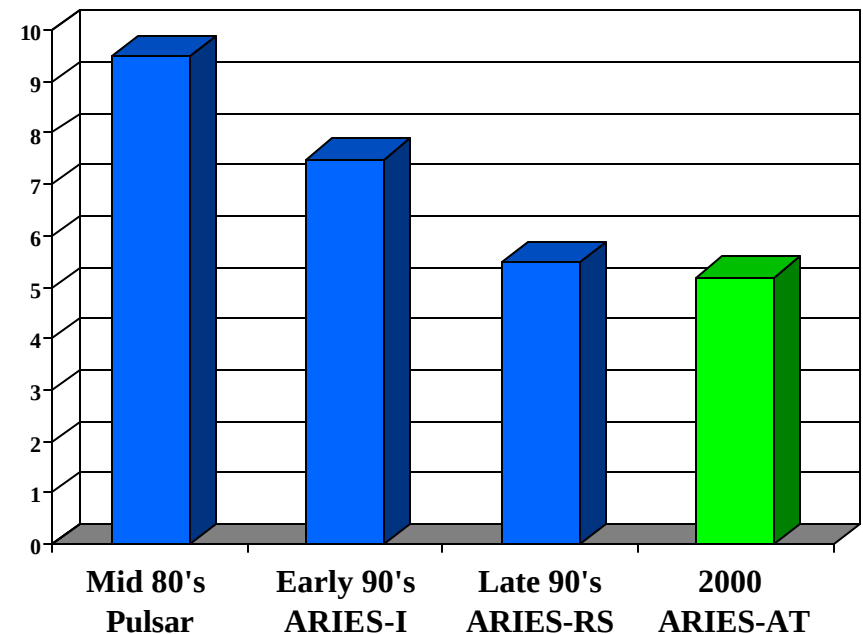


Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology

Estimated Cost of Electricity (c/kWh)



Major radius (m)



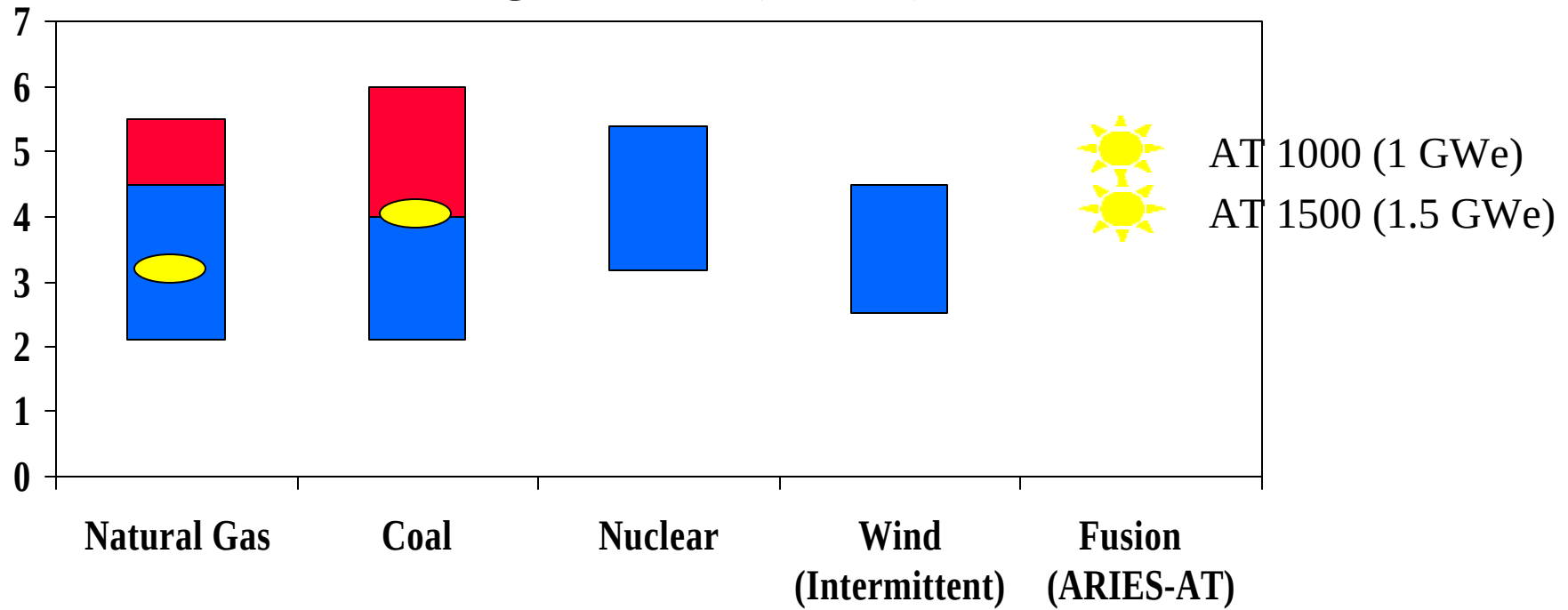
Present ARIES-AT parameters:

Major radius: 5.2 m
Toroidal β : 9.2%
Wall Loading: 4.75 MW/m²

Fusion Power 1,720 MW
Net Electric 1,000 MW
COE 5.5 c/kWh

ARIES-AT is Competitive with Other Future Energy Sources

Estimated range of COE (c/kWh) for 2020*



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.

Impact on R&D Programs

Advanced Design Program Has Had A Major Impact on Tokamak Research

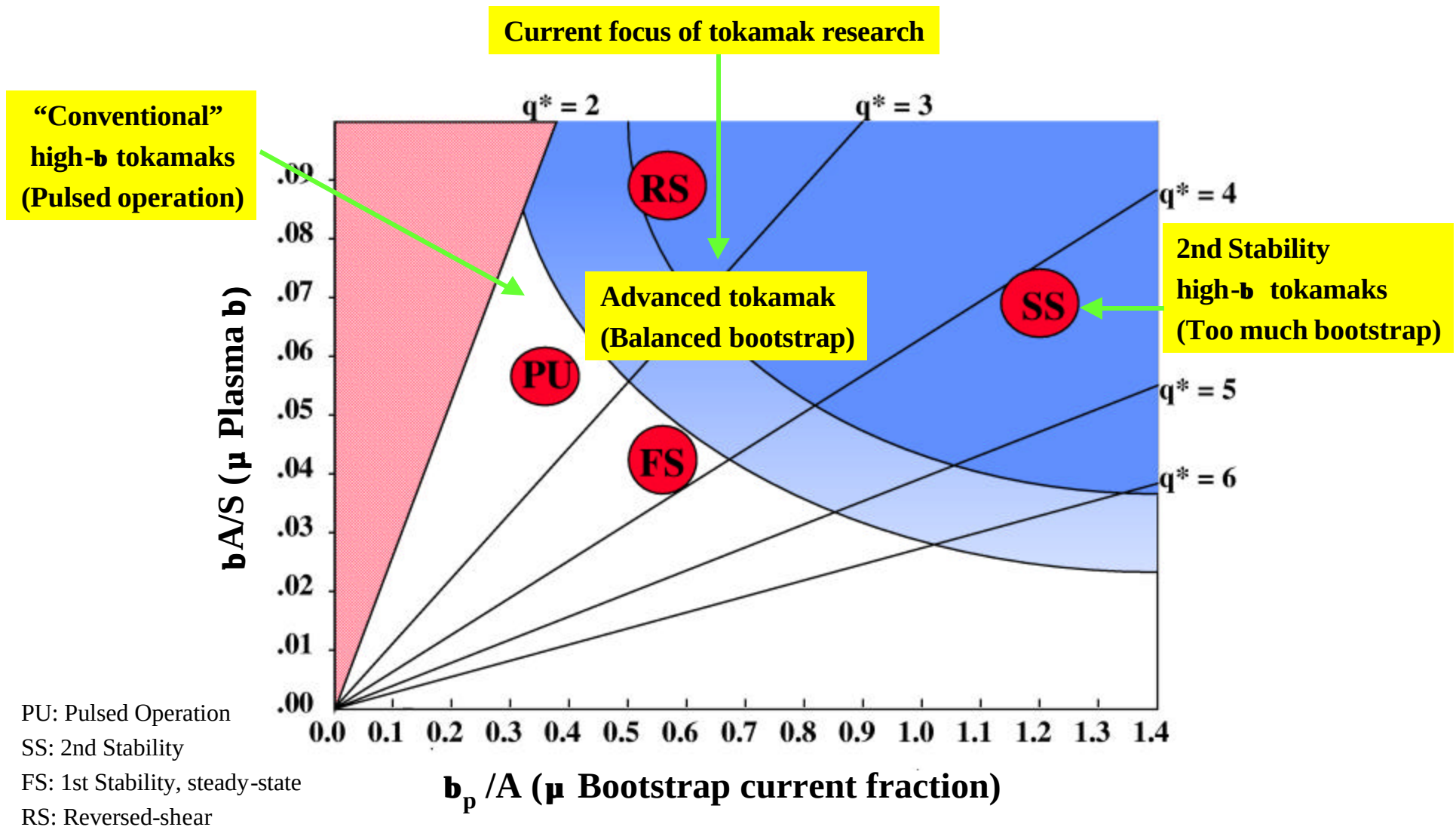
Major Physics Results

- Introduced the trade-off between plasma β and bootstrap current.
- Showed that high-field magnets can be utilized to compensate for low β .
- Showed that true benefit of 2nd Stability regime was to reduce the current-drive power not increased β .
- Demonstrated that (1) in pulsed-tokamaks the plasma β is limited by ohmic profile constraint, (2) physics of pulsed and steady-state tokamaks are essentially the same; (3) steady-state out performs pulsed operation because of technological constraints.
- Developed reversed-shear equilibria appropriate to power plants. It included a self-consistent divertor/plasma edge conditions with acceptable impact on ideal MHD, current drive, and power balance.

Impact on the Program

- ⇒ Initiation of Advanced Tokamak Research.
- ⇒ KSTAR construction and TPX experiment design were influenced significantly.
- ⇒ Major theoretical and experimental activities on advanced tokamaks
- ⇒ ARIES-RS is the present focus of advanced tokamak research (DIII-D, C-Mod, FIRE).
- ⇒ Recognition at Snowmass that any burning plasma experiments must have advanced tokamak capability.

Tokamak Research Has Been Influenced by the Advanced Design Program



Advanced Design Program Has Had A Major Impact on Alternative Concept Research

Major Scientific Results

- **Spherical Torus:** Developed the first self-consistent stability and current-drive calculations of high- β , high bootstrap current ST equilibria. Showed that high plasma elongation ($\kappa = 3$) is necessary. Showed resistive ST center-posts can be designed to operate in power-plant conditions.
- **Stellarator:** Invented a new stellarator magnetic configuration to address the issue of large size.
- **Reversed-Field Pinch:** Identified the need to operate with a highly radiative core, poloidal divertors, and an efficient current drive system so that a compact RFP can be realized.

Impact on the Program

- ⇒ NSTX is influenced by ARIES-ST
- ⇒ The next step in ST program, DTST, uses ARIES-ST as the target.
- ⇒ Initiated a large interest in compact stellarator research in US.
- ⇒ Experiments on ZT-40 with a highly radiative core and helicity-injection current-drive. ZT-P device was built to study poloidal divertors for RFPS;
- ⇒ Design and experimental program on ZT-H were modified to address these issues.

Advanced Design Program Has Had A Major Impact on Fusion Technology Research

Major Fusion Technology Results

- Introduced SiC composites as a high-performance fusion material.
- Explored gas injection and impurity radiation to reduce heat load in the divertors.
- Innovative superconducting magnet designs using plates and a structural cap (later used in ITER);
- Demonstrated benefits of RF systems (especially fast waves) for current drive and the respective launchers (e.g., folded wave-guides);
- Introduction of advanced manufacturing techniques which reduce the unit costs of components drastically.
- Emphasis on safety & environmental aspects of fusion;

Impact on the Program

- ⇒ Large world-wide research activity on SiC composites material.
- ⇒ Experiments in linear plasma machine and later in large tokamaks.
- ⇒ Current goals of magnet R&D program.
- ⇒ Spurred interest in RF current drive experiments (e.g., fast-wave current drive in DIII-D in mid 90s).
- ⇒ Application in next-generation experiments.
- ⇒ Direct impact on research on fusion materials and chamber technologies

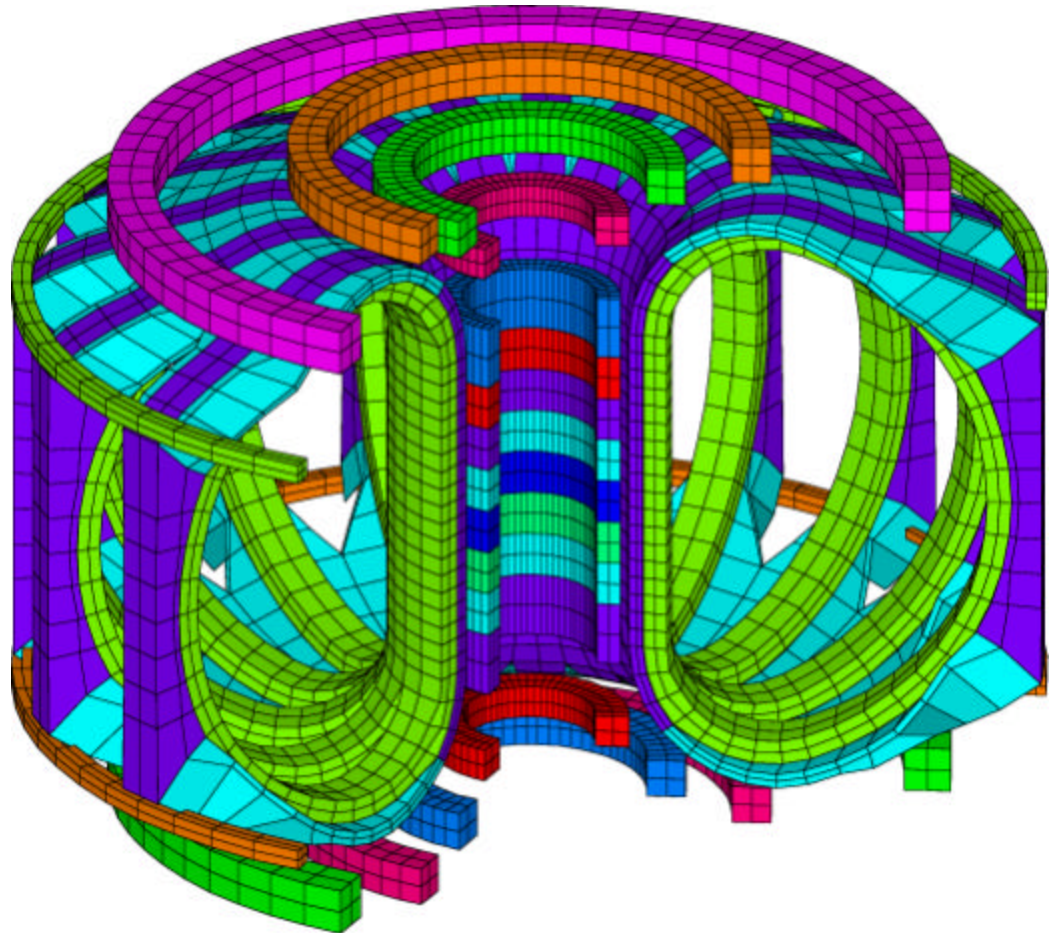
The ARIES-RS Utilizes An Efficient Superconducting Magnet Design

TF Coil Design

- 4 grades of superconductor using Nb_3Sn and NbTi ;
- Structural Plates with grooves for winding only the conductor.

TF Structure

- Caps and straps support loads without inter-coil structure;
- TF cross section is flattened from constant-tension shape to ease PF design.



Bridge to Latest Developments in Other Scientific & Technological Disciplines

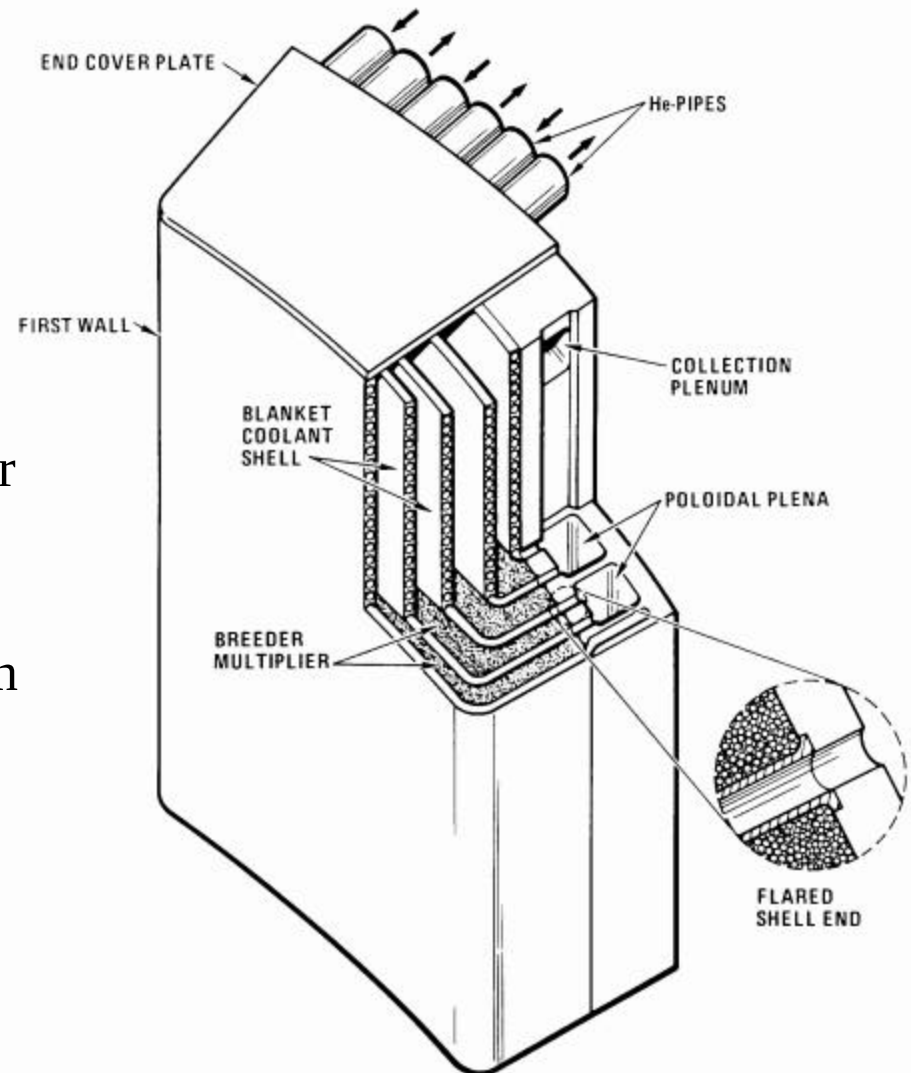
Impact of Latest Developments in Other Scientific Disciplines Are Continuously Considered.

Examples include:

- SiC Composites (Aerospace);
- Advanced manufacturing techniques (Aerospace);
- Advanced engineered material for high heat-flux components;
- High-temperature superconductors.

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

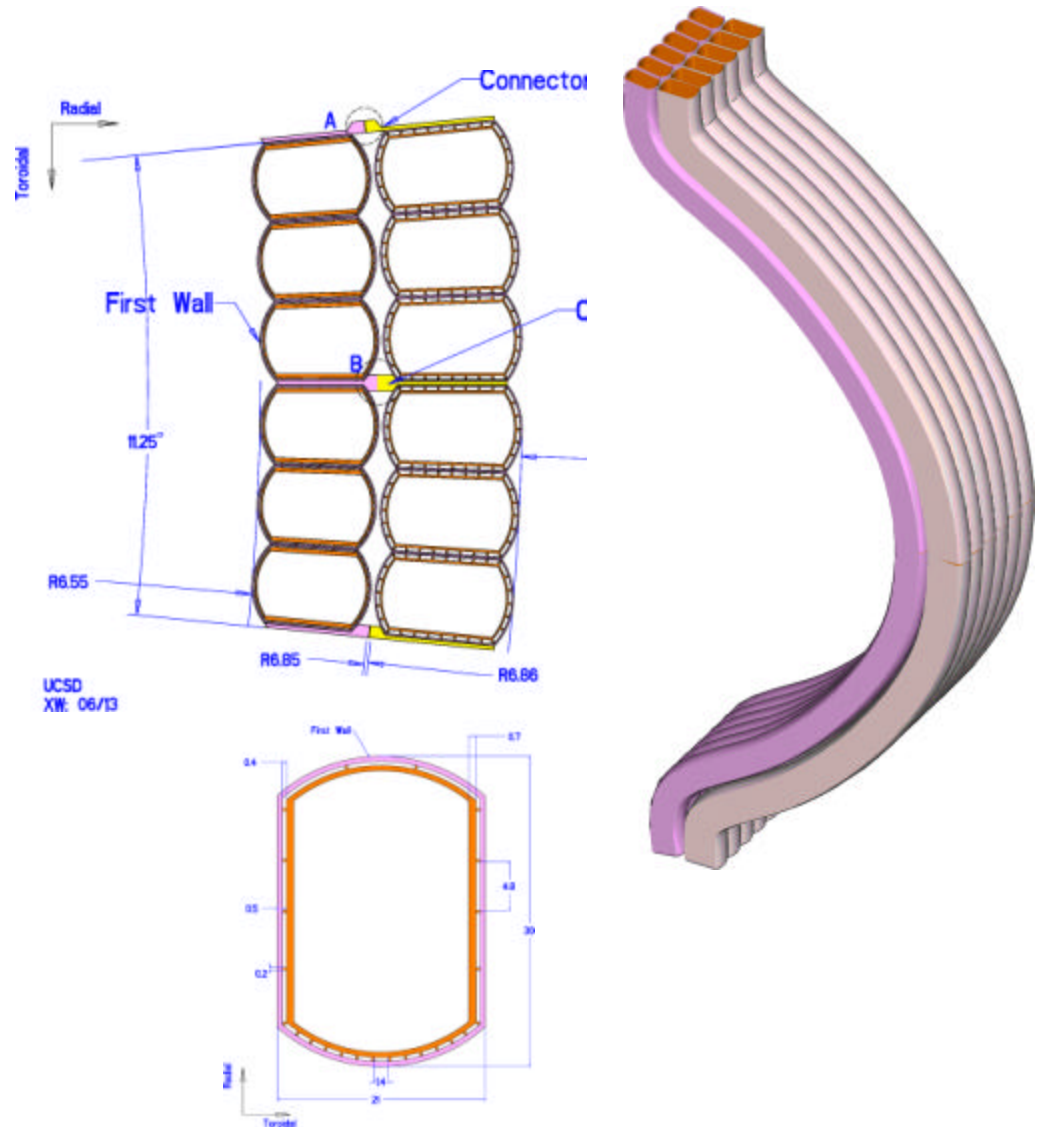
- Excellent safety & environmental characteristics (very low activation and very low afterheat).
- High performance due to high strength at high temperatures ($>1000^{\circ}\text{C}$).
- Large world-wide program in SiC:
 - * New SiC composite fibers with proper stoichiometry and small O content.
 - *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



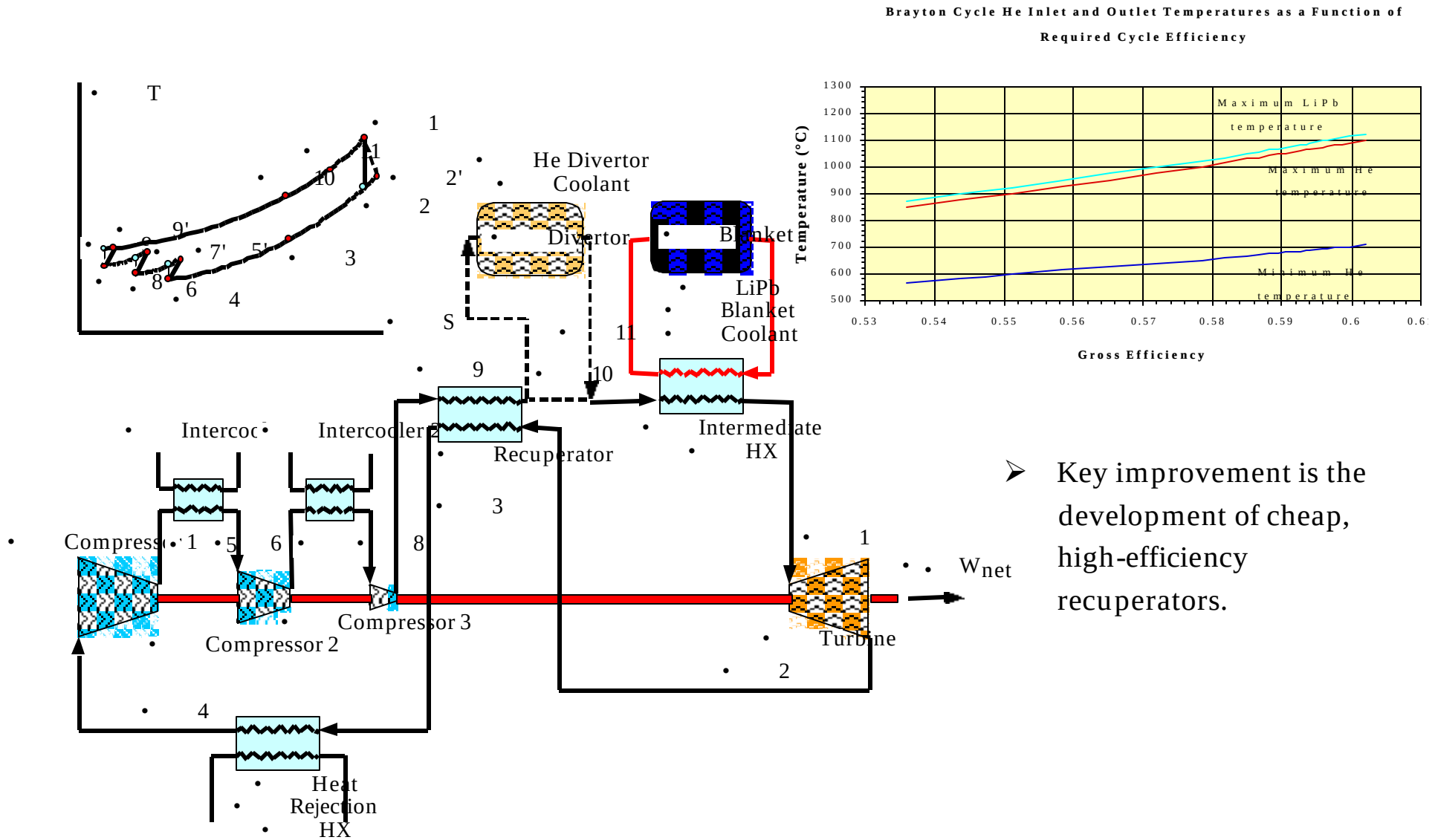
ARIES-AT²: SiC Composite Blankets

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature ($\sim 1100^{\circ}\text{C}$) while keeping SiC structure temperature below 1000°C leading to a high thermal efficiency of $\sim 60\%$.
- 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



**Publication and
ARIES-Sponsored Workshops
& Town Meetings**

ARIES Research were presented in conferences and ARIES sponsored workshop & town meetings

- Conference Presentations:
 - ARIES Papers in every IAEA fusion energy conference since 1990.
 - ARIES Papers in most SOFT conferences since 1988.
 - Invited talks and several ARIES Paper in ISFNT conferences since 1992.
 - Invited talks and ARIES sessions in every IEEE SOFE meeting since 1987.
 - Invited talks and ARIES sessions in every ANS topical meeting since 1988.

- ARIES Publications (206 papers) :

TITAN	27	Starlite	21	ARIES-AT*	16
ARIES-I	33	SPPS	7	ARIES-IFE*	8
ARIES-II/IV	6	ARIES-RS	20		
ARIES-III	23	ARIES-ST	22		
Pulsar	5	General	18		

* Submitted to IAEA, SOFT, 14th ANS and Fusion eng. & Design

Recent ARIES Town Meetings

Jan. 18-19, 2000	ORNL	International Town Meeting on SiC/SiC Design and Material Issues for Fusion Systems
May 6-7, 1998	UCSD	ARIES Town Meeting on ST Physics
June 19, 1997	UW	ARIES Town Meeting on Designing with Brittle Materials
Jan. 31, 1996	UCSD	Starlite Town Meeting on Low Aspect Ratio Spherical Tokamaks
May 10, 1995	ANL	Starlite Materials Town Meeting on structural materials
Mar. 2-3, 1995	ANL	Workshop on liquid target divertor

Recent ARIES International Workshops

March 2-3, 1995	ANL	Workshop on liquid target divertor
Mar. 17-18, 2000	UCSD	IEA Task Meeting on Socioeconomic Aspects of Fusion Power
Mar. 16-17, 2000	UCSD	US/Japan Workshop on Power Plant Studies and Advanced Technologies with EU participation
May 11-13, 1998	San Diego	1st US/Japan Workshop on Laser-Driven Inertial Fusion Energy
Mar. 3-5, 1997	UCSD	Japan-US Workshop on Fusion Power Plants (with EU&China)
Mar. 13-14, 1996	UCSD	Japan-US Workshop on Fusion Power Plants

ARIES Research in the Context of National Program

National Advanced Design Program Is a High-Leverage Research Effort

- **High Quality of Science:** Detailed and in-depth analysis is necessary to make scientific progress.
- **High-Leverage Research:** Integrated design & analysis beyond current experiments identifies key R&D Issues.
- **Community input and consensus:** An environment is created for fusion scientists to investigate fusion systems together. Team members bring in the latest information from R&D program. State-of-art analysis, innovation, and high-leverage issues are readily transferred back to the R&D program.
- **Interaction with other disciplines:** Impact of latest development in other scientific fields on fusion systems are evaluated.
- **Impact on Education:** Approximately 2/3 of the research is performed by universities (UCSD, U. Wisc., RPI, MIT). Seven students were supported by this activity last year.
- **A high-leverage niche on the international fusion program.** It is recognized internationally as a credible driving force towards an attractive end product and influences world-wide fusion research.