ARIES-AT: An Advanced Tokamak, Advanced Technology Fusion Power Plant

Presented by
Farrokh Najmabadi
University of California, San Diego,
La Jolla, CA, United States of America

IAEA 18th Fusion Energy Conference
October 4-10, 2000
Sorrento Italy

You can download a copy of the paper and the poster from the ARIES Web Site:

ARIES Web Site: http://aries.ucsd.edu/PUBLIC
Farrokh Najmabadi, Stephen C. Jardin, Mark Tillack, Rene Raffray, Ronald Miller, Lester Waganer, and the ARIES Team:

Michael C. Billone, Leslie Bromberg, Tom H. Brown, Vincent Chan, Laila A. El-guebaly, Phil Heitzenroeder, Charles Kessel Jr., Lang L. Lao, Siegfried Malang, Tak-kuen Mau, Elsayed A. Mogahed, Tom Petrie, Dave Petti, Don Steiner, Igor Sviatoslavsky, Dai-kai Sze, Allan D. Turnbull, Xueren Wang,

University of California, San Diego,
1) Argonne National Laboratory,
2) Boeing High Energy Systems,
3) General Atomics,
4) Idaho National Engineering & Environmental Lab.,
5) Massachusetts Institute of Technology,
6) Princeton Plasma Physics Laboratory,
7) Rensselaer Polytechnic Institute,
8) University of Wisconsin - Madison,
9) Forschungszentrum Karlsruhe
Electronic copy of the paper as well as all ARIES documentations are available at:

http://aries.ucsd.edu/PUBLIC

Look at under “Design Descriptions”
Directions for Optimization
ARIES Research Framework: Assessment Based on Attractiveness & Feasibility

- Periodic Input from Energy Industry
- Goals and Requirements
- Projections and Design Options
- Evaluation Based on Customer Attributes: Attractiveness
  - Balanced Assessment of Attractiveness & Feasibility
    - No: Redesign
    - Yes: Characterization of Critical Issues: Feasibility
      - R&D Needs and Development Plan

Energy Mission

Science Mission
Top-Level Requirements for Commercial Fusion Power Plants

➢ Public Acceptance:
  • 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;

➢ Reliable Power Source:
  • 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.
Translation of Requirements to GOALS for Fusion Power Plants

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.

COE has a “hyperbolic” dependence ($\propto 1/x$) and improvements “saturate” after certain limit.
There Is Little Economic Benefit for Operating Beyond ~ 5 MW/m$^2$ of Wall Load

- Simple analysis for a cylindrical plasma with length $L$:

  What we pay for, $V_{\text{FPC}}$

  Wall loading $I_w \propto 1/r$

  $\Delta$ is set by neutron mfp

  $V_{\text{FPC}} = \pi L \left( 2r\Delta + \Delta^2 \right)$

  For $r \gg \Delta$, $V_{\text{FPC}} \approx 2 \pi L r \Delta \propto 1 / I_w$

  For $r \ll \Delta$, $V_{\text{FPC}} \approx 2 \pi L \Delta^2 \approx \text{const.}$

  “Knee of the curve” is at $r \approx \Delta$

- Detailed Systems analysis from TITAN reversed-field pinch (1988 $\$$)

- High $\beta$ and cheap copper TF

- Helicity Injection (ohmic current drive)

- Freedom of choice of aspect ratio

- Optimization driven by geometrical constraints.

Hyperbolic dependence

"Knee of the curve"
There Is Little Economic Benefit for Operating Beyond 5-10 MW/m² of Wall Load

- ARIES-RS, ARIES-ST, and ARIES-AT have not optimized at the highest wall load (all operate at around 5 MW/m² peak)

- Physics & Engineering constraints cause departure from geometrical dependence e.g., high field needed for high load increases TF cost

- ARIES-AT optimizes at lower wall loading because of high efficiency.
The ARIES-RS Study Set the Goals and Direction of Research for ARIES-AT

<table>
<thead>
<tr>
<th></th>
<th><strong>ARIES-RS Performance</strong></th>
<th><strong>ARIES-AT Goals</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Economics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Power Density</strong></td>
<td>Reversed-shear Plasma</td>
<td>Higher performance RS Plasma,</td>
</tr>
<tr>
<td></td>
<td>Radiative divertor</td>
<td>SiC composite blanket</td>
</tr>
<tr>
<td></td>
<td>Li-V blanket with</td>
<td>High $T_c$ superconductors</td>
</tr>
<tr>
<td></td>
<td>insulating coatings</td>
<td></td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>610°C outlet (including divertor)</td>
<td>&gt; 1000°C coolant outlet</td>
</tr>
<tr>
<td></td>
<td>Low recirculating power</td>
<td>&gt; 90% bootstrap fraction</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Full-sector maintenance</td>
<td>Same or better</td>
</tr>
<tr>
<td></td>
<td>Simple, low-pressure design</td>
<td></td>
</tr>
<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Safety and</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>attractiveness</strong></td>
<td>Low afterheat V-alloy</td>
<td>SiC Composites</td>
</tr>
<tr>
<td></td>
<td>No Be, no water, Inert atmosphere</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radial segmentation of fusion core to minimize waste quantity</td>
<td>Further attempts to minimize waste quantity</td>
</tr>
</tbody>
</table>
ARIES-AT Parameters
<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARIES-RS</th>
<th>ARIES-AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Major toroidal radius (m)</td>
<td>5.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Plasma minor radius (m)</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Plasma elongation ($\kappa_x$)</td>
<td>1.9</td>
<td>2.2</td>
</tr>
<tr>
<td>Plasma triangularity ($\delta_x$)</td>
<td>0.77</td>
<td>0.84</td>
</tr>
<tr>
<td>Toroidal $\beta$</td>
<td>5%</td>
<td>9.2%</td>
</tr>
<tr>
<td>Electron density ($10^{20}$ m$^{-3}$)</td>
<td>2.1</td>
<td>2.3</td>
</tr>
<tr>
<td>ITER-89P scaling multiplier</td>
<td>2.3</td>
<td>2.6</td>
</tr>
<tr>
<td>Plasma current</td>
<td>11</td>
<td>13</td>
</tr>
</tbody>
</table>
## Major Parameters of ARIES-RS and ARIES-AT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARIES-RS</th>
<th>ARIES-AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-axis toroidal field (T)</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Peak field at TF coil (T)</td>
<td>16</td>
<td>11.4</td>
</tr>
<tr>
<td>Current-drive power to plasma (MW)</td>
<td>81</td>
<td>36</td>
</tr>
<tr>
<td>Peak/Avg. neutron wall load (MW/m²)</td>
<td>5.4/ 4</td>
<td>4.9/3.3</td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>2,170</td>
<td>1,755</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>0.46</td>
<td>0.59</td>
</tr>
<tr>
<td>Gross electric power (MW)</td>
<td>1,200</td>
<td>1,136</td>
</tr>
<tr>
<td>Recirculating power fraction</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>Cost of electricity (c/kWh)</td>
<td>7.5</td>
<td>5</td>
</tr>
</tbody>
</table>
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)

Present ARIES-AT parameters:
- Major radius: 5.2 m
- Toroidal $\beta$: 9.2%
- Wall Loading: 4.75 MW/m$^2$
- Fusion Power: 1,720 MW
- Net Electric: 1,000 MW
- COE: 5 c/kWh
ARIES-AT is Competitive with Other Future Energy Sources

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Natural Gas</th>
<th>Coal</th>
<th>Nuclear</th>
<th>Wind (Intermittent)</th>
<th>Fusion (ARIES-AT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPRI Electric Supply Roadmap (1/99):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Business as usual</td>
<td>4</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact of $100/ton Carbon Tax.</td>
<td>4</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


* Data from Snowmass Energy Working Group Summary.
Main Features of ARIES-AT²
(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 $\beta$ than ARIES-RS and reduced current-drive power.

- The ARIES-AT study shows that the combination of advanced tokamak modes and advanced technology leads to attractive fusion power plant with excellent safety and environmental characteristics and with a cost of electricity which is competitive with those projected for other sources of energy.
Physics Analysis
Continuity of ARIES research has led to the progressive refinement of research

**ARIES-I:**
- Trade-off of $\beta$ with bootstrap
- High-field magnets to compensate for low $\beta$

**ARIES-II/IV (2\textsuperscript{nd} Stability):**
- High $\beta$ only with too much bootstrap
- Marginal reduction in current-drive power

**ARIES-RS:**
- Improvement in $\beta$ and current-drive power
- Approaching COE insensitive of power density

**ARIES-AT:**
- Approaching COE insensitive of current-drive
- High $\beta$ is used to reduce toroidal field

Need high $\beta$ equilibria with high bootstrap

Need high $\beta$ equilibria with aligned bootstrap

Better bootstrap alignment
More detailed physics
ARIES-AT\textsuperscript{2}: Physics Highlights

- We used 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 $\beta$.
- ARIES-AT blanket allows vertical stabilizing shell closer to the plasma, leading to higher elongation and higher $\beta$.
- Detailed stability analysis indicated that $H$-mode pressure & current profiles and X-point improves ballooning stability.
- A kink stability shell ($\tau = 10$ $\text{ms}$), 1cm of tungsten behind the blanket, is utilized to keep the power requirements for $n = 1$ resistive wall mode feedback coil at a modest level.
ARIES-AT²: Physics Highlights

- We eliminated HHFW current drive and used only lower hybrid for off-axis current drive.

- Self-consistent physics-based transport simulations indicated the optimized pressure and current profiles can be sustained with a peaked density profile.

- A radiative divertor is utilized to keep the peak heat flux at the divertor at ~ 5 MW/m².

- As a whole, we performed detailed, self-consistent analysis of plasma MHD, current drive, transport, and divertor (using finite edge density, finite p’, impurity radiation, etc.)
High Accuracy Equilibria are Essential to Assess Stability of Advanced Tokamak Plasmas

ARIES-AT Equilibrium
The ARIES-AT Equilibrium is the Results of Extensive ideal MHD Stability Analysis – Elongation Scans Show an Optimum Elongation
Pressure Profiles Scans Show the Interplay Between Plasma $\beta$ and Bootstrap Alignment – Optimum Profiles are NOT at the Highest $\beta$
Vertical Stability and Control is a Critical Physics/Engineering Interface

- ARIES-AT elongation of $\kappa=2.2$ is consistent with allowed stabilizer location
Approximately 90% of feedback power is reactive power.
Variation of PF Coil Energy Measure with the Number of PF Coils for ARIES-AT

*note that inboard solenoid is fixed and is modelled as 7 coils*
Detailed Physics Modeling has been performed for ARIES-AT

- High accuracy equilibria;
- Large ideal MHD database over profiles, shape and aspect ratio;
- RWM stable with wall/rotation or wall/feedback control;
- NTM stable with LHCD;
- Bootstrap current consistency using advanced bootstrap models;
- External current drive;
- Vertically stable and controllable with modest power (reactive);
- Rough kinetic profile consistency with RS /ITB experiments, as well GLF23 transport code;
- Modest core radiation with radiative SOL/divertor;
- Accessible fueling;
- No ripple losses;
- 0-D consistent startup;
Blanket Analysis
Continuity of ARIES research has led to the progressive refinement of research

**ARIES-I:**
- SiC composite with solid breeders
- Advanced Rankine cycle

**Starlite & ARIES-RS:**
- Li-cooled vanadium
- Insulating coating

**ARIES-ST:**
- Dual-cooled ferritic steel with SiC inserts
- Advanced Brayton Cycle at $\geq 650 \, ^\circ C$

**ARIES-AT:**
- LiPb-cooled SiC composite
- Advanced Brayton cycle with $\eta = 59\%$

Many issues with solid breeders; Rankine cycle efficiency saturated at high temperature

Max. coolant temperature limited by maximum structure temperature

High efficiency with Brayton cycle at high temperature
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-AT²: 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/m² of heat load.
Moving Coordinate Analysis to Obtain Pb-17Li Temperature Distribution in ARIES-AT First Wall Channel and Inner Channel

- Assume MHD-flow-laminarization effect
- Use plasma heat flux poloidal profile
- Use volumetric heat generation poloidal and radial profiles
- Iterate for consistent boundary conditions for heat flux between Pb-17Li inner channel zone and first wall zone
- Calibration with ANSYS 2-D results
Temperature Distribution in ARIES-AT Blanket Based on Moving Coordinate Analysis

- Pb-17Li Inlet Temp. = 764 °C
- Pb-17Li Outlet Temp. = 1100 °C

- From Plasma Side:
  - CVD SiC Thickness = 1 mm
  - SiCf/SiC Thickness = 4 mm
    (SiCf/SiC k = 20 W/m-K)
  - Pb-17Li Channel Thick. = 4 mm
  - SiC/SiC Separ. Wall Thick. = 5 mm
    (SiCf/SiC k = 6 W/m-K)

- Pb-17Li Vel. in FW Channel= 4.2 m/s
- Pb-17Li Vel. in Inner Chan. = 0.1 m/s

- Plasma heat flux profile assuming no radiation from divertor
Recent Advances in Brayton Cycle Leads to Power Cycles With High Efficiency

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 intercoolers
- Turbine efficiency = 0.93
- Compressor efficiency = 0.88
- Recuperator effectiveness (advanced design) = 0.96
- Cycle He fractional $\Delta P = 0.03$
- Intermediate Heat Exchanger
  - Effectiveness = 0.9
  - $\frac{(mC_p)_\text{He}}{(mC_p)_{\text{Pb-17Li}}} = 1$

Multi-Dimensional Neutronics Analysis to Calculate Tritium Breeding Ratio and Heat Generation Profiles

- Latest data and code
- 3-D tritium breeding > 1.1 to account for uncertainties
- Blanket configuration and zone thicknesses adjusted accordingly
- Blanket volumetric heat generation profiles used for thermal-hydraulic analyses
# ARIES-AT Outboard Blanket Parameters

- Number of Segments: 32
- Number of Modules per Segment: 6
- Module Poloidal Dimension: 6.8 m
- Average Module Toroidal Dimension: 0.19 m
- First Wall SiC$_f$/SiC Thickness: 4 mm
- First Wall CVD SiC Thickness: 1 mm
- First Wall Annular Channel Thickness: 4 mm
- Average Pb-17Li Velocity in First Wall: 4.2 m/s
- First Wall Channel Re: $3.9 \times 10^5$
- First Wall Channel Transverse Ha: 4340
- MHD Turbulent Transition Re: $2.2 \times 10^6$
- First Wall MHD Pressure Drop: 0.19 MPa
- Maximum SiC$_f$/SiC Temperature: 996°C
- Maximum CVD SiC Temperature: 1009°C
- Maximum Pb-17Li/SiC Interface Temperature: 994°C
- Average Pb-17Li Velocity in Inner Channel: 0.11 m/s
Configuration & Maintenance
Cutaway of the ARIES-AT Fusion Power Core

- Central Solenoid
- PF Coils
- Cryostat
- Vacuum Pumping Ducts
- TF Coil
- First Wall & Blanket
- Vacuum Vessel
- Divertor Region
- HT Shield
- Maintenance Port
ARIES-AT Also Uses A Full-Sector Maintenance Scheme
Develop Plausible Fabrication Procedure and Minimize Joints in High Irradiation Region

1. Manufacture separate halves of the SiC\textsubscript{f}/SiC poloidal module by SiC\textsubscript{f} weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process;

2. Manufacture curved section of inner shell in one piece by SiC\textsubscript{f} weaving and SiC Chemical Vapor Infiltration (CVI) or polymer process;

3. Slide each outer shell half over the free-floating inner shell;

4. Braze the two half outer shells together at the midplane;

5. Insert short straight sections of inner shell at each end;

Brazing procedure selected for reliable joint contact area