Characteristics of Commercial Fusion Power Plants
Results from ARIES-AT Study

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

Characterization of Critical Issues: Feasibility → Yes: R&D Needs and Development Plan

Scientific & Technical Achievements → Balanced Assessment of Attractiveness & Feasibility

No: Redesign
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.
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.

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

<table>
<thead>
<tr>
<th>Economics</th>
<th>ARIES-RS Performance</th>
<th>ARIES-AT Goals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power Density</strong></td>
<td>Reversed-shear Plasma</td>
<td>Higher performance RS Plasma,</td>
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<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&lt;sub&gt;c&lt;/sub&gt; superconductors</td>
</tr>
<tr>
<td></td>
<td>insulating coatings</td>
<td></td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>610ºC outlet (including divertor)</td>
<td>&gt; 1000 ºC 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>Advanced manufacturing techniques</td>
</tr>
<tr>
<td><strong>Safety and Environmental 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>Further attempts to minimize waste quantity</td>
</tr>
<tr>
<td></td>
<td>Radial segmentation of fusion core to minimize waste quantity</td>
<td></td>
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</table>
ARIES-AT²: 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 ($\tau = 10$ 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-AT\textsuperscript{2}: 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 \(\sim 5 \text{ MW/m}^2\).
- 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.)
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.
Recent Advances in Brayton Cycle Leads to Power Cycles With High Efficiency

Key improvement is the development of cheap, high-efficiency recuperators.
ARIES-AT Also Uses A Full-Sector Maintenance Scheme
### 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>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 ($10^{20} \text{ m}^{-3}$)</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

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<tr>
<th>Parameter</th>
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<th>ARIES-AT</th>
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<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 (mill/kWh)</td>
<td>76</td>
<td>55</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)

- **Mid 80's Physics**
- **Early 90's Physics**
- **Late 90's Physics**
- **Advance Technology**

### Major radius (m)

- **Mid 80's Pulsar**
- **Early 90's ARIES-I**
- **Late 90's ARIES-RS**
- **2000 ARIES-AT**

**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: 5.5 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.


* Data from Snowmass Energy Working Group Summary.
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 \(\sim 60\%\) 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.