Status of Advanced Design Studies and Overview of ARIES-AT Study

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Electronic copy: http://aries.ucsd.edu/najmabadi/TALKS
ARIES Web Site: http://aries.ucsd.edu/ARIES
Role of Fusion in a Sustainable Global Energy Strategy

• Most of the socioeconomic studies were launched in FY 99:
  * Study of options to deploy large fusion power plant including hydrogen production and co-generation. (ORNL & Partners). Completed in 12/99. (Presentation by L. Waganer)
  * Establish the merits and address issues associated with fusion implementation (PPPL). (Presentation by J. Schmidt)
  * Macro-economics modeling of global energy market and role of fusion (PNL) (Continuation of previous work).
  * Comparison of various sources of energy based on equivalent CO$_2$ emission (U. Wisc.). (Presentation by J. Kulckinski)
National Power Plant Studies Program
Initiated Two-years Projects in 1/99

• **Fusion Neutron Source Study:**
  • Non-electric applications of fusion, specially those resulting in near-term products may lead to new clients and to additional resources for fusion.
  • A concept definition study was performed to identify promising concepts and provide necessary information for proceeding further.

• **ARIES-AT:**
  • Assess impact of advanced technologies as well new physics understanding & modeling capabilities on the performance of advanced tokamak power plants.

• **Integrated IFE Chamber Study:** (to start in 4/2000)
  • Identify and explore design window for IFE chambers.
Non-Electric Applications of Fusion Neutrons

• Typical applications ($\sim 10^{19}-10^{21} \text{ n/s}$):
  * Transmutation of fission waste (Actinides);
  * 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 ($\sim 10^{11}-10^{13} \text{ n/s}$)
  * Radioisotope production;
  * Medical radiotherapy;
  * Detection of explosives.
Key Conclusions of Neutron Source Study

• There are many different transmutation fuel cycles and many different blankets proposed.

• There is no established set of criteria. Most concepts can be re-optimized based on different criteria, so comparison is difficult.

• Work by other communities has focused on performance (cost, electricity production, burn through) not on safety, licensing, reliability, cost, etc.

• Most performance parameters mainly depend on blanket and fuel cycle choices (spectrum of external source matters little).
Key Conclusions of Neutron Source Study

- The most fundamental distinction is the existence of an external neutron source leading to critical versus sub-critical blanket operation.
  * Fission (near-term technology)
  * Fusion & accelerator (sub-critical operation and deeper burn)
- The cost of the external neutron source is an added cost. Trade-off of sub-critical operation and deeper burn versus cost difficult in the absence of established criteria. Compared to accelerators, fusion has the added difficulty of the need to breed tritium.
- This is NOT a near-term option for fusion because of the safety and licensing issues and the associated need for component data base and reliability. Same is true for accelerator-based systems.
- Both ATW and fusion-based system are technically viable long-term options.
# ARIES-RS Study Sets 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>
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<tr>
<td><strong>Power Density</strong></td>
<td>Reversed-shear Plasma</td>
<td>Higher performance RS Plasma, High T&lt;sub&gt;c&lt;/sub&gt; superconductors</td>
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<tr>
<td></td>
<td>Radiative divertor</td>
<td></td>
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<td></td>
<td>Li-V blanket with insulating coatings</td>
<td></td>
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<tr>
<td><strong>Efficiency</strong></td>
<td>610° C outlet (including divertor)</td>
<td>&gt; 1000° C coolant outlet</td>
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<tr>
<td></td>
<td>Low recirculating power</td>
<td>&gt; 90% bootstrap fraction</td>
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<tr>
<td><strong>Availability</strong></td>
<td>Full-sector maintenance</td>
<td>Same or better</td>
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<tr>
<td></td>
<td>Simple, low-pressure design</td>
<td></td>
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<tr>
<td><strong>Manufacturing</strong></td>
<td></td>
<td>Advanced manufacturing techniques</td>
</tr>
<tr>
<td><strong>Safety and</strong></td>
<td>Low afterheat V-alloy</td>
<td>SiC Composites</td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td>No Be, no water, Inert atmosphere</td>
<td></td>
</tr>
<tr>
<td><strong>attractiveness</strong></td>
<td>Radial segmentation of fusion core to minimize waste quantity</td>
<td>Further attempts to minimize waste quantity</td>
</tr>
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</table>
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.

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

⇒ Present strawman operates at the same power density as ARIES-RS, higher $\beta$ was used to reduce the peak field at the magnet.

• Reduce unit cost of components through **advanced manufacturing techniques.**
ARIES-AT\(^2\): 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 $\beta$.

- 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.)

- ARIES-AT blanket allows vertical stabilizing shell closer to the plasma, leading to higher elongation and higher $\beta$. 
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.
- High LiPb outlet temperature (~1100°C) and high thermal efficiency of ~60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
Recent Advances in Brayton Cycle Leads to Power Cycles With High Efficiency

- Key improvement is the development of cheap, high-efficiency recuperators.
ARIE-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>0.86</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>2.25</td>
</tr>
<tr>
<td>ITER-89P scaling multiplier</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Plasma current</td>
<td>11</td>
<td>13</td>
</tr>
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</table>
## Major Parameters of ARIES-RS and ARIES-AT

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<th>ARIES-AT</th>
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<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</td>
</tr>
<tr>
<td>Current-drive power to plasma (MW)</td>
<td>81</td>
<td>25</td>
</tr>
<tr>
<td>Peak/Avg. neutron wall load (MW/m²)</td>
<td>5.4/4</td>
<td>4.7/3.8</td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>2,170</td>
<td>1,720</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>0.12</td>
</tr>
<tr>
<td>Cost of electricity (mill/kWh)</td>
<td>76</td>
<td>53</td>
</tr>
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</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

**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: 5.3 c/kWh
The Integrated IFE Study Will Identify and Explore the Design Window for IFE chambers & Define R&D Needs

- Target designs
- Chamber concepts

Characterization of target yield
Characterization of chamber response

Chamber environment

Target fabrication, injection, and tracking

Final optics & chamber propagation

Driver

Chamber R&D:
- Data base
- Critical issues

Assess & Iterate
• The scope and relative size of the MFE and IFE studies in FY01 depends on program budget and outcome of congressional process.