THE ARIES

TOKAMAK REACTOR STUDIES

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for The ARIES Team

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ARIES Is a Community-Wide Study

Collaborations

ARIES

UCLA
ANL
GA
LANL
MIT
PPPL
RPI
MDA
ORNL
INEL
U. Wis.
There Are Four ARIES Tokamak Reactor Designs

- ARIES-I is based on modest extrapolations in physics and on technologies that may be developed in 5 to 30 years mostly by programs outside fusion (Completed 6/90).

- ARIES-III is an advanced fuel (D-\(^3\)He) tokamak reactor (Completed 8/91).

- ARIES-II/IV is based on greater extrapolations in physics e.g., 2nd stability (To be completed 6/92).

**Goal:** A combination of economic competitiveness, a high level of safety assurance, and attractive environmental features.
Principal Results of ARIES-I Study

• Within the constraint of operating in the first MHD stability regime, a high aspect-ratio (∼4.5) tokamak reactor operating with a high bootstrap-current fraction is the most attractive steady-state tokamak, particularly because current-drive power and recirculating power can be minimized.

• The use of very low-activation materials, such as silicon-carbide (SiC) composites, will have the greatest impact on the attractiveness of fusion power. Fusion reactors utilizing these materials can achieve a high level of safety and a minimal burden of waste disposal.

• Advances in the design of superconducting coils greatly simplify the engineering design and economic performance of fusion power reactors.
Principal Results of ARIES-III Study

- The physics of D-\(^{3}\)He tokamak reactors are very demanding. A D-\(^{3}\)He tokamak reactor requires a highly reflective first wall (or coating), a small first-wall hole fraction, and a low value of ash particle to energy confinement times, \(\tau_{ash}/\tau_{E}\).

- If physics parameters can be achieved, the engineering features are attractive (with the exception of the in-vessel components, which are subjected to high particle and heat fluxes).

- The safety and environmental features of the ARIES-III design are attractive. However, proper choice of low-activation materials has a much larger impact on the safety aspects of a fusion reactor than the choice of the fusion fuel cycle. (e.g., using SiC composites reduces the radioactivity inventory by about 7 orders of magnitude compared to that of a stainless steel structure. By contrast, the use of D-\(^{3}\)He fuel reduces the radioactive inventory by less than one order of magnitude compared to using D-T fuel.)
The ARIES-II/IV Activity Is Examining Reasonably-Consistent Advances in Physics to Improve the Economics of the Reactor and to Reduce the Required Extrapolation in Technology.
ARIES-II/IV Designs Are Based on the Same Plasma Core but Two Distinct Fusion Power Cores

ARIES-II will use vanadium as the structural material and liquid lithium as the coolant to assess the potential of low-activation metallic blankets.

ARIES-IV will use SiC composite as the structural material, He as the coolant, Li$_2$O as the solid breeder (instead of Li$_2$ZrO$_3$ in ARIES-I) and probably no Be multiplier. The aim is to further improve the safety features of ARIES-I and achieve an inherently safe reactor.
The ARIES-I Design Activity Has Highlighted High Leverage Areas

In order to improve the reactor economics over ARIES-I:

1. Increase $\beta$ to reduce magnet cost $\implies$ 2nd stability.

2. $\sim 100\%$ bootstrap-current fraction to reduce current-drive cost $\implies$ 2nd stability.

3. Higher fusion power density (wall loading) to reduce blanket and shield cost $\implies$ First-wall neutron and heat flux concerns?

4. Improve safety and environmental features to achieve LSA 1.
   $\implies$ For ARIES-IV, use alternate breeders, eliminate Be and W armor of divertor plate,

- Operation in the second MHD stable regime with the constraint of $\sim 100\%$ bootstrap current (i.e., moderate plasma $\beta$) leads to a highly attractive tokamak reactor with small recirculating power.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>ITER-CDA</th>
<th>ARIES-I</th>
<th>ARIES-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</td>
<td>2.8</td>
<td>4.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Plasma major radius (m)</td>
<td>6.0</td>
<td>6.75</td>
<td>5.6</td>
</tr>
<tr>
<td>Plasma minor radius (m)</td>
<td>2.15</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Toroidal field on axis (T)</td>
<td>4.85</td>
<td>11.3</td>
<td>7.6</td>
</tr>
<tr>
<td>Toroidal field on the coil (T)</td>
<td>11.5</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>Plasma current (MA)</td>
<td>22</td>
<td>10</td>
<td>5.6</td>
</tr>
<tr>
<td>Plasma beta</td>
<td>4%</td>
<td>1.9%</td>
<td>3.4%</td>
</tr>
<tr>
<td>Fusion power density (MW/m³)</td>
<td>1</td>
<td>3.8</td>
<td>6.3</td>
</tr>
<tr>
<td>Neutron wall loading (MW/m²)</td>
<td>1</td>
<td>2.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>
The ARIES-IV Fusion Power Core
Comparison of Physics Requirements of ARIES Designs with present Experimental Achievements

<table>
<thead>
<tr>
<th>Aspect ratio</th>
<th>ARIES-I</th>
<th>DIII-D</th>
<th>ARIES-III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.0</td>
<td>4.5</td>
<td>2.5 - 5.3</td>
</tr>
<tr>
<td>Elongation</td>
<td>1.8</td>
<td>1.8</td>
<td>1.2 - 2.6</td>
</tr>
<tr>
<td>( \tau / \tau_L )</td>
<td>2.6</td>
<td>2.0 - 3.6</td>
<td>7.6</td>
</tr>
<tr>
<td>Beta</td>
<td>1.9%</td>
<td>4% - 12%</td>
<td>24%</td>
</tr>
<tr>
<td>Troyon Coeff.</td>
<td>3.2</td>
<td>3.5 - 6.5</td>
<td>15</td>
</tr>
<tr>
<td>Poloidal Beta</td>
<td>2.8</td>
<td>1.0 - 5.2</td>
<td>5.4</td>
</tr>
<tr>
<td>( \varepsilon \beta_p )</td>
<td>0.65</td>
<td>0.5 - 1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>( I_{BS} / I_p )</td>
<td>68%</td>
<td>10% - 50%</td>
<td>120%</td>
</tr>
<tr>
<td>Core ( \tau_p / \tau_E )</td>
<td>4</td>
<td>&gt; 4</td>
<td></td>
</tr>
</tbody>
</table>

* From T. Simonen, GA (The stripped ranges for DIII-D were not achieved simultaneously.)
Implications of ARIES Research for a Next-Step, Advanced Tokamak Experiment

• The current drive cost and recirculating power has a major impact on the attractiveness of a reactor. The only “non-speculative” and efficient current drive is bootstrap current and it is not totally free! (trade-off against plasma beta).

• Plasma parameters are inter-dependent. An attractive reactor requires optimization of a self-consistent plasma as opposed to optimization of a single plasma parameter (i.e., a plasma with highest $\beta$ does not necessarily result in an optimum reactor).

↓

• Best tokamak is one with an MHD state with highest $\beta$ that is consistent with the constraint of $\sim$100% bootstrap current, acceptable confinement, acceptable ash exhaust, etc.
Advanced Tokamak Experiment (ATX): Size, Scale, and Scope

Should Advanced Tokamak Experiment (ATX) be aimed at providing a database for ITER or be complementary to that of ITER?

- We believe that ATX should be complementary to ITER. Furthermore, ATX should be of such a scale that the ATX physics data base can be directly extrapolated to DEMO.

Plasma Physics: \( \text{ITER} + \text{ATX} \Rightarrow \text{DEMO} \)

It is difficult to justify an expensive ATX that requires yet another large machine to validate its physics data base for DEMO (with the exception of \( \alpha \)-particle effects).
Implications of ARIES Research for the Technology Program

- Achieving the potential safety and environmental features of fusion should be the fundamental goals of the fusion technology and material research.

- Material development program should emphasize materials that have other applications (e.g., aerospace and automotive industries) to ensure that these materials are developed and have reasonable costs.

- An extensive fusion technology and material R&D should begin NOW in order for these technologies to be tested in near-full scale in ITER and be ready for the fusion DEMO.

- The industry should be a major participant in the fusion technology R&D so that the industrial infrastructure would be in place for the DEMO.
U.S. Magnetic Fusion System Studies Plans

- **PULSAR Project**
  - Identify the extent to which pulsed tokamak reactors can make an attractive and competitive commercial power plants.

- **STARLITE Project**
  - Investigate objectives, performance requirements, prerequisite data base, and design features for the Fusion Demonstration Power Plant.
  - Provide strategies, facility requirements, and testing needs for the Fusion Demonstration Power Plant (DEMO).