THE ARIES-II AND ARIES-IV
SECOND-STABILITY TOKAMAK REACTORS

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ARIES Is a Community-Wide Study

Collaborations

ARIES

MIT

PPPL

RPI

MDA

UCLA

ANL

GA

LANL

ORNL

INEL

U. Wis.

MDA
There Are Four ARIES Tokamak Reactor Designs

• ARIES-I is based on modest extrapolations in physics and on technology which has a 5 to 20 year development horizon often 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.
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 Will Be 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. $\sim100\%$ 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, eliminate W armor of divertor plate, use alternate breeders, and eliminate Be.
The Trade-off Among MHD, Bootstrap, and Current Drive Determines the Optimum Reactor

- **ARIES-II:** Second stability operation \((q_o = 2.)\).

\[ \downarrow \]

- Requires profile control (FWCD and NBCD)

\[ \downarrow \]

- Maximize bootstrap fraction, aiming at \(I_{BS}/I_p = 1 \ (\epsilon \beta_P \approx 2.2\sqrt{\epsilon})\).

- However: \(\beta \approx 0.5(\epsilon \beta_p) \frac{\epsilon}{q_o^2 q_*^2} (1 + \kappa^2)\)

\[ \downarrow \]

- Beta value would be modest even though normalized beta \((\beta_N)\) is high. \(\beta \approx 0.044\epsilon^{3/2} (1 + \kappa^2)\)

\[ \Rightarrow \] Optimum design has moderate \(\beta\), **BUT** the current drive power is small!
## Major Parameters of ARIES Reactors

<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 Tokamak Fusion Core
Physics Features of ARIES-II/IV

- 2st stability regime ($C_T \sim 6$ from MHD analysis) with self-consistent plasma profiles for transport, current-drive, stability, and edge-plasma analysis.

- Steady-state operation by ICRF fast waves and lower hybrid ($\sim 25$ MW) and self-consistent bootstrap ($\sim 80\%$).

- Confinement scaling consistent with present data-base ($\tau_E = H\tau_L$, $H \sim 3$)

- Single-null gas-target divertor are being pursued. High-recycling poloidal divertor are alternatives.
Comparison of Physics Requirements of ARIES Designs with present Experimental Achievements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARIES-I</th>
<th>DIII-D*</th>
<th>ARIES-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</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>2</td>
<td>4</td>
<td>&gt; 4</td>
</tr>
</tbody>
</table>

* From T. Simonen, GA (The stripped ranges for DIII-D were not achieved simultaneously.)
Engineering Features of ARIES-II

- ARIES-II blanket is made of vanadium alloy structural material with liquid lithium as the coolant and tritium breeder.

- ARIES-II blanket utilizes an insulating layer (TiN) which will reduce the MHD pressure drop by a factor of 20 (< 1 MPa).

- Because of the low pressure drop, the blanket design has been optimized toward heat transfer and simplicity.

- Because of high coolant outlet temperature, a gross thermal efficiency of ~45% is estimated.
Engineering Features of ARIES-IV

- ARIES-IV blanket has used the ARIES-I design experience.

- ARIES-IV blanket is a He-cooled design with SiC/SiC composite structural material, and Li$_2$O solid tritium breeder and Be neutron multiplier.

- Low-activation RAFS with B$_4$C are used as the shield material.

- An advanced Rankine power conversion cycle as proposed for future coal-burning plants (49% gross efficiency).

- By eliminating the Li$_2$ZrO$_3$ breeder and W coating of the divertor plate, and minimizing Be inventory, a high level of safety assurance is projected for ARIES-IV.
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 approaching $\sim 100\%$ bootstrap current, acceptable confinement, acceptable ash exhaust, etc.
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.
Magnetic Fusion System Studies Plans

• ARIES Project will be concluded by 8/92.

• 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).