THE ARIES-III

D–$^3$He TOKAMAK REACTOR STUDY

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and The ARIES Team

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ARIES Is a Community-Wide Study
Primary Objectives

- Develop self-consistent design approaches for D–$^3$He tokamak reactors. Determine potential economic, safety, and environmental features of this class of tokamak reactors.

- Identify critical physics and technology issues for D–$^3$He tokamak reactors.

- Identify key issues that are specific to D–$^3$He tokamak reactors.

- Identify key areas that use of D–$^3$He fuel has resulted in improvements in reactor performance.
Physics Requirements for D–³He Tokamak Reactors Are Demanding

- \[ P_f \propto \frac{\langle \sigma v \rangle}{T^2} (\beta B^2)^2 \]

<table>
<thead>
<tr>
<th></th>
<th>DT</th>
<th>D–³He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (keV)</td>
<td>10–20</td>
<td>50</td>
</tr>
<tr>
<td>(\langle \sigma v \rangle/T^2) (normalized)</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>(\beta B^2) (% T^2)</td>
<td>(\geq 200)</td>
<td>(\geq 1000)</td>
</tr>
</tbody>
</table>

↓

- A D–³He reactor requires high \(\beta\), high \(B\), and high \(T\).

↓

- High \(T\) and high \(B\) result in a highly radiative plasma (synchrotron and bremsstrahlung).

↓

- Plasma power balance window is small.
The D–$^3$He Tokamak Plasma Power Balance Is Dominated by Radiation

- High $T$ and high $B$ result in a highly radiative plasma:*  

\[ P_{brem} \propto Z_{eff} n_e^2 T_e^{1/2} \]
\[ P_{syn} \propto n_e^{1/2} T_e^{5/2} B^{5/2} \sqrt{1 - R_{syn}} \]
\[ R_{syn} = (1 - f_h) (1 - \sqrt{2\epsilon_o Z^* \omega_c \rho}) \]

\[ f_h \equiv \text{first-wall "hole" fraction.} \]
\[ \rho \equiv \text{first-wall electrical conductivity.} \]

* Fully relativistic formulas are used in actual calculations.

\[ \rightarrow \text{Requires highly reflective first wall, small "hole" fraction, and stringent ash exhaust limit.} \]
The Power Balance Window for a D–$^3$He Tokamak Plasma Is Small.
Electrical Resistivity of Some Material

![Graph showing electrical resistivity vs. temperature for different materials: SS, V15Cr5Ti, W, Be, Al, Cu. The resistivity is measured in $10^{-9} \Omega m$.](image_url)
Implications of Physics Requirements

- The small power balance window implies:
  
  ⋆ Highly reflective first wall and small hole fraction are required.

  First wall should be coated with Cu, Be, or W.

  ⋆ Ash exhaust limits are stringent:

  \[
  \frac{\tau_{p}^{\text{ash}}}{\tau_{E}^{\text{bulk}}} \leq 1 - 1.5 \text{ for 1st stability regime.}
  \]

  \[
  \frac{\tau_{p}^{\text{ash}}}{\tau_{E}^{\text{bulk}}} \leq 2 - 3 \text{ for 2nd stability regime.}
  \]

- Start-up in D–³He requires a large amount of auxiliary power. Start-up with a DT phase is preferred.

- Thermal stored energy in the plasma is \( \sim 10 \) times that of a DT reactor. Thermal load during a disruption is a major issue.
First Stability D–³He Tokamak Reactors Appear Unattractive

• Since $P_{syn} \propto B^{2.5}$, there is an optimum in the field ($\sim 21$ T). High $\beta$ ($\sim 10\%$) is required leading to low aspect ratio ($\sim 3$), high current ($\sim 70$ MA), and low bootstrap fraction ($\sim 45\%$).

• The ARIES study considered first stability D–³He reactor assuming
  * Core $\tau_{p}^{ash} / \tau_{E}^{bulk} = 1$;
  * Synchrotron current drive;
  * Solid state direct conversion of synchrotron power;
The Trade-off Among Transport, MHD, Bootstrap, and Current Drive Determines the Optimum Second-Stability Reactor

- **ARIES-III**: Second stability \((q_o = 2)\) with core \(\tau_{p}^{ash}/\tau_{E}^{bulk} = 2\).

- Requires strict profile control; high plasma temperature exclude use of FWCD leading to NBI current drive.

- Requires very high \(\beta\), therefore, low \(q_*/q_o\).

- Relax kink stability requirement:
  - \(q_o/q_* = 1/1.2\) (requires stabilization of kink modes through helical feedback coils)
  - \(\epsilon \beta_p \simeq 1.8\) leading to bootstrap overdrive
    (requires driving current in both directions).

\[\Rightarrow\] High \(\beta\) but kink unstable and large driven current (in both directions).
ARIES-III D–³He Reactor Requires Strict Plasma Profile Control

- $p$ and $j_\phi$ profiles are optimized for high $\beta$ at $\epsilon\beta_p \sim 1$.

- $n$ profile is chosen to minimize bootstrap current overdrive.
The ARIES-III D–³He Tokamak Reactor
### ARIES-III Major Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Second Stability Operation</strong></td>
<td></td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>3.0</td>
</tr>
<tr>
<td>Plasma major radius (m)</td>
<td>7.5</td>
</tr>
<tr>
<td>Plasma minor radius (m)</td>
<td>2.5</td>
</tr>
<tr>
<td>Toroidal field on axis (T)</td>
<td>7.6</td>
</tr>
<tr>
<td>⇒ Plasma current (MA)</td>
<td>30</td>
</tr>
<tr>
<td>⇒ Toroidal beta</td>
<td>24%</td>
</tr>
<tr>
<td>Electron density (\times 10^{20} \text{ m}^{-3})</td>
<td>3.3</td>
</tr>
<tr>
<td>Ion density (\times 10^{20} \text{ m}^{-3})</td>
<td>2.1</td>
</tr>
<tr>
<td>Electron temperature (keV)</td>
<td>53</td>
</tr>
<tr>
<td>(Z_{eff})</td>
<td>2.0</td>
</tr>
<tr>
<td>Neutron wall loading (MW/m²)</td>
<td>0.1</td>
</tr>
<tr>
<td>Net electric power (MWe)</td>
<td>1000</td>
</tr>
<tr>
<td>⇒ Recirculating power fraction</td>
<td>0.24</td>
</tr>
</tbody>
</table>
The Physics Requirements of ARIES-III Are Severe

Confinement

- \( \tau_p^{ash}/\tau_E^{bulk} = 2 \ (\tau_E = 12 \text{ s}) \).

VERSUS

- Confinement enhancement \( H_{ITER-P} \approx 7.2 \)

Equilibrium & Stability

- 2nd stability operation at \( \beta = 24\% \ (C_T = 15) \).

BUT

- Feed-back stabilization of kink modes is required.

- Very precise profile control is necessary to ensure ballooning stability.
Requirements of Kink-Stabilization Feedback Coils

- Ten coils are required, each capable of carrying 1% of the plasma current (360 kA). Copper conductor in each coil is 1 cm $\times$ 60 cm in cross section. Coils are located between the shield and the vacuum vessel.

- Coils are helical with $n = 1$ and $m = 1$ geometry.

- Coils are broken into four independently controllable toroidal segments.

- In each toroidal segment, every pair of coils are formed into saddle coils for control of the $n = 1$, $m = 1$ and $m = 2$ modes.

- There are 20 sets of electrical leads and coolant circuits. Coils interfere with access to first wall and shield and should be demountable.

$\Rightarrow$ The maintenance-related complications arising from this coil set are severe.
Physics Features of ARIES-III

**Impurity control**

- Because transport power is low ($H$ factor is assumed to be high), high-recycling divertors appear feasible.
- Peak heat flux is $\sim 5 \text{ MW/m}^2$ and $T_e < 30 \text{ eV}$.
- Target armor is 4 mm of W. Can withstand thermal load of only **one** disruption.

**Fueling**

- Both pellet and compact-tori injection are considered. Issues:
  - $^3\text{He}$ pellet production and injection.
  - CT acceleration power.
Physics Features of ARIES-III

Current drive

- Required for control of current profile for MHD stability.
- High efficiency is required.
- 6-MeV NBI for seed current (48 MW).
- 3-MeV NBI for reverse current (146 MW).
- Current drive efficiency: 0.06 A/W.
- NBI based on RFQ with system efficiency of 0.68.
- Beam-plasma reaction produces 21.6 MW of fusion power ($^3$He beams not feasible because of $^3$He$^-$ source problems and low CD efficiency of 0.02 A/W).
FPC Engineering Requirements

- High reflectivity first wall to $\mu$m waves (1 to 30 THz synchrotron radiation)

- High heat flux removal capability for first wall and divertor ($\sim$2–3 MW/M$^2$ on average) consistent with high temperature operation needed to achieve a high thermal conversion efficiency.

- Radiation of the bulk of the fusion power ($\sim$80–90%) in order to lower the divertor heat load to the same level as in a DT reactor

- Low Activation materials and coolant to permit shallow land burial of the radioactive waste.
## Surface Heat Load Comparison

<table>
<thead>
<tr>
<th></th>
<th>D–T</th>
<th>D–³He</th>
<th>Ratio of D–³He/D–T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fusion Power (MW)</td>
<td>3,000</td>
<td>3,000</td>
<td>1</td>
</tr>
<tr>
<td>Neutron Power (MW)</td>
<td>2,400</td>
<td>~100</td>
<td>~0.04</td>
</tr>
<tr>
<td>Plasma Power (MW)</td>
<td>600</td>
<td>~2,900</td>
<td>~5</td>
</tr>
<tr>
<td>Nominal Radiation Fraction</td>
<td>30%</td>
<td>80%–90%</td>
<td>~3</td>
</tr>
<tr>
<td>Power to Divertor (MW)</td>
<td>420</td>
<td>300–600</td>
<td>~1</td>
</tr>
<tr>
<td>Power to First Wall as</td>
<td>180</td>
<td>2,400–2,700</td>
<td>~15</td>
</tr>
<tr>
<td>Surface Heating (MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Engineering Features of ARIES-III

- Low activation modified HT-9 is chosen for the shield because it produces the thinnest shield and qualifies as shallow-land burial.

- Modified HT-9 is also used for the first wall.

- Organic Coolant HB-40 (Diphenol) at relatively low pressure (2.6 MPa).

- First wall is coated by 1.45 mm of Be. Thickness is set to absorb thermal load of one disruption.

- 100 µm of W layer is used in between steel and Be to prevent interaction of Be and steel.

- Steam cycle for thermal conversion ($\eta_{th} \approx 0.44$).
An ARIES-III FPC Module
Reasons for Selection of Organic Coolant for the ARIES-III Reactor

- High heat flux on the first wall ($\sim 2.5 \text{ MW/m}^2$).
- First wall coated with Cu, Be, or W.
- He: poor heat removal capability.
- Liquid metal: activation, MHD effects.
- Water: high pressure, low thermal efficiency.
- Organic*: low pressure, high thermal efficiency.

* Reduced neutron yield for D-$^3$He cycle reduces radiolytic decomposition and allows organic coolants to be used.
### Major Parameters of the ARIES-III FPC

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant pressure (MPa)</td>
<td>2.6</td>
</tr>
<tr>
<td>Inlet temperature (°C)</td>
<td>350</td>
</tr>
<tr>
<td>Outlet temperature (°C)</td>
<td>425</td>
</tr>
<tr>
<td>Coolant velocity (m/s)</td>
<td>16.5</td>
</tr>
<tr>
<td>First-wall thickness (mm)</td>
<td>0.6</td>
</tr>
<tr>
<td>Max. first wall temperature (°C)</td>
<td>545</td>
</tr>
<tr>
<td>Max. Be temperature (°C)</td>
<td>630</td>
</tr>
<tr>
<td>Outboard shield thickness (m)</td>
<td>0.8</td>
</tr>
<tr>
<td>Max. Shield temperature (°C)</td>
<td>500</td>
</tr>
</tbody>
</table>
Details of ARIES-III Blanket Design
Details of ARIES-III First Wall Design
ARIES-III Magnets Are Based on Near-Term Technology

- $B_{\text{coil}} = 14 \text{ T.}$
- Use of a ferritic shield results in ferromagnetic reduction of ripple.
- 20 shell-like coils with large out-of-plane strength. Support caps to handle fault conditions.
- High-strength structural alloy (700 MPa), high-strength stabilizer, and demountable cryostats.
- Large energy margin in the innermost turns to absorb nuclear heating of the DT start-up.
- PF coils have similar conductor and structure.
- PF coil design is driven by the need to provide and maintain plasma current during the start-up.
- Pulsed losses in the TF and PF system due to helical feed-back control coils need to be determined.
Safety and Waste Disposal Features of ARIES-III Are Very Attractive

- Compared to DT, D–³He fuel results in 1/20 of neutron power, \(\sim 1/10\) of afterheat, and 1/4 the activation for comparable structure.

- After 30 full power years of operation, shield qualifies as class-A waste after a 25-year cool down period.

- ARIES-III produces 11 g of tritium per day which is reinjected and burned in the reactor.

- Activation of coolant is negligible but disposal of the decomposed coolant is an issue.

- ARIES-III is passively safe.

- Significant safety credits for COE are possible.
Very Low Activation Material is the KEY to Achieving Potential Attractive Features of Fusion

Critical Dose at 1 km (rem)
First Wall, Blanket, and shield

* From S. K. HO, U.C. Berkeley
Principal Results of ARIES-III Study

- Realization of D–^3^He tokamak reactors requires major advances in physics.
  
  ★ First-stability D–^3^He power plants appear impractical.
  
  ★ Second-stability plants require operation at very high $\beta$ and plasma is kink unstable.

  ★ Considerably better energy confinement (high $H$ factor), very low $\tau_p^{ash}/\tau_E^{bulk}$ or efficient active ash pumping, a means of plasma fueling, and efficient current drive are required.

- A parallel path to achieving the attractive safety and environmental features of fusion is the development of very-low-activation material for D–T reactors.
Principal Results of ARIES-III Study

- The engineering of the first wall and divertor is difficult:
  - High surface heat flux,
  - High reflectivity for µm waves (1-30 THz synchrotron radiation),
  - High thermal load of a disruption.

- Use of D–³He fuel results in simplification of the fusion power core (no breeding blanket).

- The radiation-damage lifetime of the first wall and shield is longer than the plant lifetime.

- Magnets can be located closer to the plasma.

- Low-pressure, high thermal efficiency organic coolant can be used because of low neutron yield of D–³He cycle.

- The reactor is passively safe and waste materials qualify for shallow-land burial under the U.S. Code of Federal Regulations.