THE ARIES

TOKAMAK REACTOR STUDY

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and The ARIES Team

Presented at
Princeton Plasma Physics Laboratory
November 15, 1991
ARIES Is a Community-Wide Study

Collaborations:
- UCLA
- ANL
- GA
- LANL
- ORNL
- INEL
- MIT
- PPPL
- RPI
- MDA
- U. Wis.

ARIES
The ARIES Study Has Three Primary Objectives

- Develop several design approaches for an attractive tokamak reactor with varying degrees of extrapolation in physics & technology.

- Determine the potential economics, safety, and environmental features of this range of possible tokamak reactors.

- Identify physics and technology areas with the highest leverage for achieving the safest, most Environmentally attractive, and economic tokamak reactor.
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).

- ARIES-III is an advanced fuel (D-³He) tokamak reactor.

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

Goal: A combination of economic competitiveness, a high level of safety assurance, and attractive environmental features.
A New Technology (*FUSION*)

Can Penetrate the Market *only if*

It Is Significantly Better than

Any Existing Technology (*FISSION*)
The KEY to Fusion Success is Attractive Safety and Environmental Features

\[
\text{Cost of Electricity (cents/kWh)} \propto \frac{FCR (C_{FPC} + C_{BOP}) + C_y}{p_f}
\]

\(C_{FPC}\): Cost of the nuclear core. For fission, \(C_{FPC} \ll C_{BOP}\). Very difficult for fusion to win with a cheaper nuclear core. But, fusion loses heavily if the cost of fusion core is high.

\(C_{BOP}\): Cost of the Balance of Plant; the major part of the direct capital cost of the plant. Fission requires “N-stamp” components. Fusion with enhanced safety can eliminate “N-stamp” requirements and reduce \(C_{BOP}\) considerably.
The KEY to Fusion Success is Attractive Safety and Environmental Features

Cost of Electricity (cents/kWh) $\propto \frac{FCR(C_{FPC} + C_{BOP}) + C_y}{p_f}$

*FCR*: Fixed Charge rate. It depends on interest rate and construction time. Public concerns and licensing delays have increased the construction time for fission. Fusion with enhanced safety has a major advantage.

*C_y*: Annual cost of fuel, replacement of components, operation and maintenance, and waste disposal. Fusion with enhanced environmental features has the advantage in waste disposal.

*p_f*: Plant availability. Fusion is far more complex than fission. But, a large contributor to fission plant shut down is failure of the safety-related equipment!
Potential attractive Safety and Environmental Features of Fusion

Waste Disposal:

Fission requires geological waste disposal. Fusion reactor waste can qualify for Class-C shallow-land burial by using low-activation structural materials (e.g. ferritic steels, vanadium alloys, SiC).

Accidental Release of Radioactivity Inventory:

The radioactivity inventory in a fission reactor is large. By proper choice of material, the radioactivity inventory of a fusion reactor can be reduced substantially. Through care in design, the impact of accidents can be reduced (both fission and fusion).
Radioactivity Levels in Fusion Reactors

- Low-activation materials reduce the activity level by 6 orders of magnitude.
ARIES-I: a DT, 1st Stability Tokamak Reactor
The Trade-off Among MHD, Bootstrap, and Current Drive Determines the Optimum Reactor

• **ARIES-I:** First stability and “conventional” (inefficient) current drive (FWCD or NBCD).

  \[
  \implies
  \]

• Minimize driven current and maximize bootstrap fraction.

  \[
  \implies
  \]

• Operate at high aspect ratio and raise \( q_o \). However: \( \frac{\beta q_o^2}{\epsilon} \propto \frac{1}{\epsilon \beta_p} \).

  \[
  \implies
  \]

• \( \beta \) is low, requiring high \( B \) to achieve reasonable fusion power density which scales as \((\beta B^2)^2\).

\[\implies\] Optimum design has high \( A \), low \( I_p \), high \( \epsilon \beta_p \), and high \( B \) but low \( \beta \).
The Same Level of Analyses and Trade-off Is Applied to All Aspects of Plasma Engineering

- Vertical stability and poloidal-field stored energy (determines plasma elongation and triangularity for a given aspect ratio).

- Current drive (driven plus bootstrap current density must match the equilibrium current density).

- Edge Physics (requires self-consistent particle and heat fluxes between edge and core plasma; higher core plasma temperature and lower density to improve current drive efficiency versus higher core plasma density to achieve adequate ash exhaust and acceptable divertor target heat flux and sputtering erosion).

- Transport (high energy confinement versus small ash accumulation; start-up, ignition, and burn utilizing current drive power as auxiliary heating).
The ARIES-I Tokamak Reactor
### Major Parameters of ARIES-I

<table>
<thead>
<tr>
<th>Aspect ratio</th>
<th>4.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma major radius (m)</td>
<td>6.75</td>
</tr>
<tr>
<td>Plasma minor radius (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Toroidal field on axis (T)</td>
<td>11.3</td>
</tr>
<tr>
<td>Toroidal field on the coil (T)</td>
<td>21</td>
</tr>
<tr>
<td>Plasma current (MA)</td>
<td>10</td>
</tr>
<tr>
<td>Neutron wall loading (MW/m²)</td>
<td>2.5</td>
</tr>
<tr>
<td>Net electric power (MWe)</td>
<td>1000</td>
</tr>
<tr>
<td>Net Plant Efficiency</td>
<td>0.39</td>
</tr>
</tbody>
</table>
The Physics of ARIES-I Is Close to Our Present Experimental Database

- Low current ($\sim 10$ MA), high aspect ratio (4.5), low beta ($\sim 2\%$), and high field ($B_o \sim 11$ T, $B_{coil} \sim 21$ T).

- 1st stability regime ($\beta = 1.9\%$, $C_T = 3.2$ from MHD analysis) with self-consistent plasma profiles for transport, current-drive, stability, and edge-plasma analysis.

- Steady-state operation by ICRF fast waves (100 MW, 140 MHz) and self-consistent bootstrap (68%).

- Confinement scaling consistent with present data-base ($\tau_E = H\tau_L$, $H \sim 2.6$)

- High-recycling poloidal divertors.
### ARIES-I Plasma Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toroidal beta ($C_T = 3.2$)</td>
<td>1.9%</td>
</tr>
<tr>
<td>Boot-strap fraction</td>
<td>68%</td>
</tr>
<tr>
<td>On-axis $q_o$</td>
<td>1.3</td>
</tr>
<tr>
<td>$q_\psi$</td>
<td>4.5</td>
</tr>
<tr>
<td>$\kappa_{95} \ (\kappa_x)$</td>
<td>1.6 (1.8)</td>
</tr>
<tr>
<td>Electron density ($\times 10^{20} \ \text{m}^{-3}$)</td>
<td>1.45</td>
</tr>
<tr>
<td>Electron temperature (keV)</td>
<td>20</td>
</tr>
<tr>
<td>Core-plasma radiation fraction</td>
<td>0.52</td>
</tr>
<tr>
<td>Energy confinement time (s)</td>
<td>2.4</td>
</tr>
<tr>
<td>H-factor (ITER89P)</td>
<td>2.6</td>
</tr>
<tr>
<td>Core $\tau_p/\tau_E$</td>
<td>4</td>
</tr>
</tbody>
</table>
Folded Wave-Guide Launcher

- Made of SiC composite with 0.02 mm Cu coating.

- Power = 4 MW; $E_{Max} \sim 36$ kV/cm.
The Engineering Features of ARIES-I Are Advanced in order to Achieve a Safe, Attractive Reactor

- Advanced superconductor (Nb$_3$Sn) toroidal-field magnets.

- ARIES-I blanket is a He-cooled design with SiC composite structural material, and Li$_2$ZrO$_3$ solid tritium breeders.
  
  ★ Composites are high strength, high temperature structural materials with very low activation and very low decay afterheat.

- An advanced Rankine power conversion cycle as proposed for future coal-burning plants (49% gross efficiency).
Irradiation data for SiC Composites are not available. Data exists only for bulk material and SiC fibers separately.

For bulk material:
- Negligible swelling which also saturates at low fluences;
- Negligible loss in strength;
- No visible void or bubble formations.

Recent theoretical micromechanics analyses indicate that damage energy in SiC is considerably higher than metallic alloys, resulting in a considerably longer life time for the first wall.
The ARIES-I Fusion Power Core Modules
Internals of an ARIES-I FPC Module

Structure: SiC Composite

Coolant: 10-MPa Helium

Breeder: Li$_2$ZrO$_3$

Outlet coolant temperature: 650 $^\circ$C

Pumping power: 50 MW
The ARIES-I FPC Module Configuration Is Developed Based on Discussions with Industry
The ARIES-I TF Magnet:  
Conductor Is Available in Small Samples  
Structural Steel Is Available Commercially

\[ B_{\text{coil}} = 21 \text{ T} \]

Conductor: Nb\text{\textsubscript{3}}Sn and NbTi
Graded spatially with \( B \).

Stabilizer: CuNb
carries structural loads

Structure: Incoloy 908 Steel

Maximum stress: 900 MPa

Stored energy: 126 GJ
Safety and Waste Disposal Features of ARIES-I Are Distinctly Attractive for Fusion

• Low-activation, low-afterheat material is used throughout the FPC.

• All ARIES-I reactor components qualify for Class-C waste disposal.

• The decay heat in ARIES-I blanket is 2 to 3 orders of magnitude lower than low-activation metallic blankets.

• Significant safety credits for COE are possible.
ARIES-I Safety Analysis
ARIES-I FPC Maintenance Is Performed Through Vertical Lift

I. Removal of Upper PF Coil Assembly
ARIES-I FPC Maintenance Is Performed Through Vertical Lift

II. Removal of Upper TF Torque Shell
ARIOES-I FPC Maintenance Is Performed Through Vertical Lift

III. Removal of an FPC Module as a Complete Unit
Comparison of Economics of ARIES Designs with that of Fission PWR

Cost of Electricity, COE (mill/kWh)

<table>
<thead>
<tr>
<th>Design</th>
<th>COE (mill/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIES-I</td>
<td>65</td>
</tr>
<tr>
<td>ARIES-II</td>
<td>52*</td>
</tr>
<tr>
<td>TITAN</td>
<td>50</td>
</tr>
<tr>
<td>Coal</td>
<td>50</td>
</tr>
<tr>
<td>Fission</td>
<td>78**</td>
</tr>
</tbody>
</table>

* No N-Stamp

** Present PWR
Principal Results of ARIES-I Study

• For steady-state, 1st stability reactors with NBI or ICRF current drive:

  ★ High aspect ratio and moderate plasma current are optimum.

  ★ High magnetic field reduces the cost of electricity.

• To maximize safety and environmental features of fusion reactors:

  ★ Helium cooling, SiC composites, low-activation tritium breeder material, and low tritium inventory are preferred.
Principal Results of ARIES-III Study

- Major advances in physics of tokamak are required to achieve an attractive D-\(^3\)He tokamak reactor:

  - Second stability operation at very high \(\beta\) (kink unstable);
  - Considerably better energy confinement (high \(H\) factor), very low \(\tau_p^{ash}/\tau_E^{bulk}\), efficient active ash pumping, and efficient current drive.

- Key direction for achieving the attractive safety and environmental features of fusion is development of low-activation materials rather than advanced fuels.
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.
Preliminary ARIES-II/IV Results

We have examined tokamak reactors with $A = 3$ to $4$, $\kappa = 1.8$, and $B_{\text{max}} = 16$ T:

- At higher $A$, even though $\beta$ is lower, the fusion power density $[\propto (\beta B^2)^2]$ is higher because of $1/R$ dependence of $B$. The COE is insensitive to the value of $A$ at present level of analyses. The technology of higher $A$ appears to be less difficult (divertor heat flux, peak-to-average heat and neutron flux on the first wall).

- 2nd stability equilibria examined for ARIES-II/IV appear to be very stable against vertical plasma motion (appears to be insensitive to $A$). Higher plasma elongations are possible.

- The startup and achievement of 2nd stability state are critical issues and are under study. Because of the lower plasma current, high-$A$ operation may be favored.
## Major Parameters of ARIES-I and -IV Reactors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ARIES-I</th>
<th>ARIES-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect ratio</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Plasma major radius (m)</td>
<td>6.75</td>
<td>6.35</td>
</tr>
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<td>1.5</td>
<td>1.4</td>
</tr>
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<td>Toroidal field on axis (T)</td>
<td>11.3</td>
<td>8.6</td>
</tr>
<tr>
<td>Toroidal field on the coil (T)</td>
<td>21</td>
<td>16</td>
</tr>
<tr>
<td>Plasma current (MA)</td>
<td>10</td>
<td>5.7</td>
</tr>
<tr>
<td>Plasma beta</td>
<td>1.9%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Fusion power density (MW/m³)</td>
<td>3.8</td>
<td>5.3</td>
</tr>
<tr>
<td>Neutron wall loading (MW/m²)</td>
<td>2.5</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Implications of ARIES Research for a Next-Step, ADVANCED TOKAMAK EXPERIMENT (ATX)

- 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 $\beta$ is 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.
Implications of ARIES Research for ATX: Choice of Aspect Ratio

- ARIES-I research indicates that optimum 1st stability tokamak reactor has high $A$, low $I$, and high bootstrap-current fraction.
- Preliminary ARIES-II/IV results indicate that the reactor performance is insensitive to the choice of aspect ratio. Technology of high-$A$ reactors appears to be less demanding. The start-up is a critical issue and may favor low $I$ and high $A$.

\[ \downarrow \]

- At present, the high-$A$ ($A \simeq 4 - 5$) option is more attractive:
  1. 1st stability reactors optimizes at high $A$.
  2. Preliminary results indicate that 2nd stability reactors may also optimize at high $A$ (or insensitive to $A$).
  3. High-$A$ regime has not be explored in a large-scale experiment (indications and trends from present machines are encouraging). A high-$A$ experiment will explore a new physics regime (opportunities or challenges?)
Advanced Tokamak Experiment (ATX): Size, Scale, and Scope

Should Advanced Tokamak Experiment (ATX) be aimed at providing a database for ITER or 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.

\[ \text{Physics: } \text{ITER} + \text{ATX} \implies \text{DEMO} \]

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).
Advanced Tokamak Experiment (ATX): Duration of the Discharge

- Existence of steady “state” \( \leq \tau \)
- Physics of steady “state” \( 3 - 10 \tau \)
- Physics of steady “operation” \( 10 - 100 \tau \)
- Technology (practicality) of steady “operation” \( \) system failure

★ There are three class of time constants:
1. \( \tau \) for plasma physics phenomena;
2. \( \tau \) for plasma response to “outside control knobs”;
3. \( \tau \) for failure in plasma support technologies.
Comparison of Physics Requirements of ARIES Designs with present Experimental Achievements*

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

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