The ARIES Designs for a Tokamak Power Plant

With particular emphasis on the ARIES-I and PULSAR Designs

presented by

S.C. Jardin

Princeton University
Plasma Physics Laboratory

Princeton University AST 558 Seminar Series
February 28, 2005
Outline

• Overview of the ARIES studies
  • Description of ARIES-I
  • Description of PULSAR
  • Relation of ARIES-I and PULSAR to the other ARIES designs
  • Comparison of ARIES-I and PULSAR
  • Some of the lessons learned from the studies
  • Summary and conclusions
• **Advanced Reactor Innovation Evaluation Study**
  - ~ 10 year program to identify and begin evaluation of attractive concepts for a Magnetic Fusion Energy (MFE) power plant
  - Led by Profs. R. Conn and F. Najmabadi (UCLA/UCSD)
  - Involved over 50 fusion scientists and engineers from about 15 institutions…University, Laboratory, Private sector

• **Documented 7+ tokamak power plant designs**


**ARIES-I**
First stability

**ARIES-II/IV**
Second stability

**ARIES-RS**
Reversed Shear

**ARIES-III**
Advanced Fuels

**ARIES-AT**
Advanced P&T

**PULSAR**
Pulsed operation

**ARIES-ST**
Spherical Torus
Philosophy of the ARIES Studies

A new technology (FUSION) can penetrate the market only if it is significantly better than any existing technology (FISSION)

• Attractive Safety Features
  – Eliminate “N-stamp” requirements (extensive, expensive design certification)
  – Low radioactive inventory (no 3-mile island or Chernobyl)
  – Minimal weapons proliferation and security costs

• Attractive Environmental Features
  – Waste disposal advantages – “Class-C” shallow-land burial (no Yucca Mountain)

• The assumption is that if these advantages are factored into the “true cost”, then fusion will have an advantage over fission
  – (Corollary is that the designs must be such as to keep these advantages)

• The physics and engineering assumptions used in the ARIES designs were sometimes very aggressive in order to get an attractive design:
  – “Theoretically possible”, not necessarily “experimentally demonstrated”
Outline

• Overview of the ARIES studies

• Description of ARIES-I

• Description of PULSAR

• Relation of ARIES-I and PULSAR to the other ARIES designs

• Comparison of ARIES-I and PULSAR

• Some of the lessons learned from the studies

• Summary and conclusions
ARIES-I
First-Stability Regime, Steady State Plasma
MHD Stable to kink modes without a Conducting Wall

ARIES-PULSAR
STARLITE

- ARIES-I design was to have “present day” physics ("first stability regime"), aggressive engineering, but keeping safety and environmental advantages

- Because RF current drive is relatively inefficient, the fraction of self-generated current (bootstrap current) must be large...68% in ARIES-I

- The constraint of "first stability" and high bootstrap current leads to relatively low $\beta = 1.9\%$, and modest normalized $\beta_N = 3.0$

- Since fusion power $\sim \beta^2B^4$, this is compensated by high $B$ (21 T at coil, 11.3 T at plasma center)*

R = 6.75 m, a = 1.5 m,
$B_T = 11.3$ T, $I_P = 10$ MA

1 GW net power

*(Redesign, A-1’, has 16 T and 9 T)
Engineering features of the ARIES-I design:

- Advanced superconductor Nb$_3$Sn alloys toroidal field magnets producing 21 (16) T at magnet and 11.3 (9) T at plasma center

- ARIES-I blanket is He-cooled (at 10 MPa) design with SiC composite structural material, and Li$_2$ZrO$_3$ solid tritium breeders with beryllium neutron-multiplier
  - SiC 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).

- Folded wave-guide launcher made of SiC composite with 0.02 mm Cu coating (for RF current drive)

- Fusion power core modular for easy maintenance using a vertical lift approach
### Major Parameters of ARIES-I

<table>
<thead>
<tr>
<th>Parameter</th>
<th>A-1’</th>
<th>PULSAR</th>
<th>STARLITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio</td>
<td>4.5</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>Major Radius (m)</td>
<td>6.75</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Vertical Elongation κ</td>
<td>1.8</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>10.2</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Toroidal Field on Axis (T)</td>
<td>11.3</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Toroidal beta</td>
<td>1.9%</td>
<td>1.9%</td>
<td></td>
</tr>
<tr>
<td>Neutron Wall load (MW/m²)</td>
<td>2.5</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Fusion power (MW)</td>
<td>2564</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net electric power (MW)</td>
<td>1000</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Net plant efficiency</td>
<td>39%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- High A to decrease $I_p$ and divertor heat loads, and increase $f_{BS}$.
- Required for power balance.
- Minimizes PF energy, vertically stable.
- Provides adequate confinement.
- At limit of advanced alloy conductor.
- At first stability limit without wall.
- 20-MW/m² lifetime.
- 97 MW ICRF CD power.
- Same for all ARIES designs.
- Advanced Rankine steam power cycle with 49% efficiency.
ARIES-I
First-Stability Regime, Steady State Plasma
MHD Stable with no Conducting Wall

Troyon Limit: \[ \beta \leq C_T \left( \frac{\mu_0}{40\pi} \right) \left( \frac{I_P}{a B_T} \right) \]

or,
\[ \left( \frac{\beta}{\varepsilon} \right) \left( \varepsilon \beta_p \right) \leq \left( \frac{C_T}{20} \right)^2 \left( 1 + \kappa^2 \right) \]

Bootstrap fraction: \[ \frac{I_{BS}}{I_P} = \frac{1}{\varepsilon^{1/2}} \left( \varepsilon \beta_p \right) C_{BS} \]

it follow that \[ \left( \frac{\beta}{\varepsilon} \right) \leq \frac{1}{\varepsilon^{1/2} \frac{I_{BS}}{I_P}} \frac{C_{BS}}{\frac{C_T}{20}} \left( 1 + \kappa^2 \right) \]

Bootstrap alignment: Need to have \( q_0 > 1 \) for \( I_{BS}/I_P > 0.5 \) to avoid local bootstrap overdrive. This tends to lower \( C_T \)

\[ \Rightarrow \text{tradeoff between high } \beta \text{ and high Bootstrap fraction} \]

\[ A = R/a = 4.5, \quad I_{BS}/I_P = 0.68, \quad \beta = 1.9\%, \quad q_0 = 1.3 \]
Outline

• Overview of the ARIES studies
• Description of ARIES-I
• Description of PULSAR
• Relation of ARIES-I and PULSAR to the other ARIES designs
• Comparison of ARIES-I and PULSAR
• Some of the lessons learned from the studies
• Summary and conclusions
Objectives of the PULSAR study

- Study the feasibility and potential features of a tokamak with a pulsed mode of plasma operation as a fusion power plant.

- Identify trade-offs which lead to the optimal regime of operation.

- Identify critical and high-leverage issues unique to a pulsed-plasma tokamak power plant.

- Compare steady-state and pulsed tokamak power plants.

R=8.6 m, a = 2.15 m, 
$B_T = 7.5 \text{ T}$, $I_p = 15 \text{ MA}$

1 GW net power
• The loop voltage induced by the “inductive” current-drive system is constant across the plasma (stationary state):

$$\frac{\partial \vec{B}}{\partial t} = 0 \implies \nabla \times \vec{E} = 0 \implies \vec{E} = \frac{V_L}{2\pi} \nabla \phi$$

– In this stationary state, plasma current-density profiles (induced and bootstrap) are determined by $n$ and $T$ profiles;

$$\vec{J} = \frac{V_L}{2\pi R\eta(n,T)} + J_{BS}(n,T)$$

– Pressure profile is $n \times T$

• Thus, Equilibrium is completely determined from $n(\psi)$, $T(\psi)$, $I_P$

– No additional freedom to tailor the current profile to improve stability limits
It follows that the current-density profile cannot be tailored to achieve the highest possible $\beta$
- $\beta_N$ is limited to $\leq 3.0$ (for most favorable profiles...broad)
- Bootstrap fraction is not large ($\sim 30\%$ to $40\%$, maximum)
- Second stability operation is not possible

A large scan of stable ohmic equilibrium was made and a fit to the data base was used in the systems analysis

$$\beta_N = \frac{\beta a B_T}{I_P}$$

$q^* = \frac{B_T \pi a^2 (1 + \kappa^2)}{RI_P}$
Power Flow in a Pulsed Tokamak

- Utilities require a minimum electric output for the plant to stay on the grid
- Grid requires a slow rate of change in introducing electric power into the grid
- Large thermal power equipment such as pumps and heat exchangers cannot operate in a pulsed mode. In particular, the rate of change of temperature in the steam generator is ~ 2°C/min in order to avoid boiling instability and induced stress.

Therefore, Steady Electric Output is Required and an Energy storage system is needed.
PULSAR Energy Storage System

• An external energy storage system which uses the thermal inertia is inherently very large:
  – During the burn, $T_{\text{co coolant}} > T_{\text{storage}}$
  – During the dwell, $T_{\text{co coolant}} < T_{\text{storage}}$
  – But the coolant temperature should not vary much. Therefore, thermal storage system should be very large

• PULSAR uses the outboard shield as the energy storage system and uses direct nuclear heating during the burn to store energy in the shield;
  – This leads to a low cost energy storage system but the dwell time is limited to a few 100’s of seconds
Energy is accumulated in outer shield during burn phase, regulated by mass flow control during dwell phase.
PULSAR cycle

- Plasma physics sets lower limit on dwell time;
  - upper limit set by thermal storage system.
- Burn time determined through trade-off between size of OH system and number of cycles.
  - COE insensitive to burn times between 1 and 4 Hrs

\[ \tau_D \sim 200 \text{ sec} \]
\[ \tau_B \sim 9000 \text{ sec} \]
## Pulsar Dwell Time Calculation

<table>
<thead>
<tr>
<th>Time Event</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Rampup time</td>
<td>54 s</td>
</tr>
<tr>
<td>Plasma ignition time,</td>
<td>53 s</td>
</tr>
<tr>
<td>Plasma de-ignition time</td>
<td>38 s</td>
</tr>
<tr>
<td>Plasma shutdown time</td>
<td>54 s</td>
</tr>
<tr>
<td><strong>Total Dwell time:</strong></td>
<td><strong>200 s</strong></td>
</tr>
</tbody>
</table>

- **Burn time:** 9000 s
- **Number of cycles:** 2,700 / year
PULSAR magnet system

- The PULSAR TF magnet system is similar to the old ITER design
- OH solenoid is located between the TF coil and the bucking cylinder
- Shear panels are used between the TF coils
- Inner legs of the TF coils are keyed together to support the shear loads
- Because of the elaborate key system, the supportable stress in the inner leg of the TF coils is reduced

=> ~15% Lower Toroidal field strength than in ARIES I
# Major Parameters of PULSAR

<table>
<thead>
<tr>
<th></th>
<th>ARIES</th>
<th>PULSAR</th>
<th>STARLITE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect Ratio</td>
<td>4.0</td>
<td>(4.5)</td>
<td>Optimizes at slightly lower A since ( f_{BS} ) does not weigh as heavily</td>
</tr>
<tr>
<td>Major Radius (m)</td>
<td>8.5</td>
<td>7.9</td>
<td>Required for power balance</td>
</tr>
<tr>
<td>Vertical Elongation ( \kappa )</td>
<td>1.8</td>
<td>1.8</td>
<td>Minimizes PF energy, vertically stable</td>
</tr>
<tr>
<td>Plasma Current (MA)</td>
<td>13</td>
<td>10</td>
<td>Provides adequate confinement</td>
</tr>
<tr>
<td>Toroidal Field on Axis (T)</td>
<td>6.7</td>
<td>9</td>
<td>Lower due to cyclic PF induced stresses</td>
</tr>
<tr>
<td>Toroidal beta</td>
<td>2.8%</td>
<td>1.9%</td>
<td>First stability limit without wall, lower ( \beta_p )</td>
</tr>
<tr>
<td>Neutron Wall load (MW/m²)</td>
<td>1.3</td>
<td>2.0</td>
<td>20-MWy/m² lifetime</td>
</tr>
<tr>
<td>Net electric power (MW)</td>
<td>1000</td>
<td>1000</td>
<td>Same for all ARIES designs</td>
</tr>
</tbody>
</table>
ITER-like design with current driven by OH-coils + Bootstrap current

**Troyon Limit:**

\[
\left( \frac{\beta}{\varepsilon} \right) \left( \varepsilon \beta_p \right) \leq \left( \frac{C_T}{20} \right)^2 \left( 1 + \kappa^2 \right)
\]

\[C_T = 3.0\]

Operate at higher \( I_p \) (lower \( \beta_p \)) to maximize \( \beta/\varepsilon \)

- However, no freedom in current profile…no non-inductive current drive
  - Current profile \( J \) determined from \( T \) and \( n \) profiles by stationary constraint
    \[
    \frac{\langle \eta(J - J_{BS}) \cdot B \rangle}{\langle B \cdot \nabla \phi \rangle} = \frac{V_L}{2\pi}
    \]
  - Using this constraint, stability boundaries can be mapped out
    - Depend only on \( \varepsilon, q^*, \) and density and temp. profile form factors

9000 s burn with 200 s OH recharge, during which thermal reservoir is tapped

\[A = R/a = 4, \ I_{BS}/I_p = .34, \ \beta = 2.8\%, \ q_0 = 0.8\]
Outline

- Overview of the ARIES studies
- Description of ARIES-I
- Description of PULSAR
- Relation of ARIES-I and PULSAR to the other ARIES designs
- Comparison of ARIES-I and PULSAR
- Some of the lessons learned from the studies
- Summary and conclusions
## Reactor Operating Modes

<table>
<thead>
<tr>
<th></th>
<th>1ST STABILITY REGIME-wall stabilization not required</th>
<th>2ND STABILITY REGIME-wall stabilization of kink modes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STEADY STATE</strong></td>
<td>MODERATE $\beta$ MODERATE $\beta_p$ ARIES-I</td>
<td>HIGH $\beta$ HIGH $\beta_p$ ARIES RS, AT, ST</td>
</tr>
<tr>
<td><strong>PULSED</strong></td>
<td>HIGH $\beta$ LOW $\beta_p$ PULSAR</td>
<td>NOT POSSIBLE</td>
</tr>
</tbody>
</table>
Dimensionless Parameter Space

\[ \frac{\beta}{\varepsilon} \times \frac{2}{(1+\kappa^2)} \text{ vs } \varepsilon \beta_p \]

for Tokamak Reactor Regimes

\[ \text{REVERSED SHEAR} \]

\[ \text{ARIES-I} \]

\[ \text{PULSAR} \]

\[ \text{DIII-D} \]

\[ \text{ARIES-AT} \]

\[ \text{ARIES-ST} \]

\[ \text{ITER} \]

\[ \text{TFTR, DIII-D} \]

\[ \text{advanced tokamak regime} \]

Bootstrap current \( \rightarrow \)

\[ \beta/\varepsilon \times \frac{2}{(1+\kappa^2)} \]

\[ \varepsilon \beta_p \]
Both the ARIES-I and PULSAR operating modes have demonstrated stationary high performance on DIII-D.
Outline

• Overview of the ARIES studies
• Description of ARIES-I
• Description of PULSAR
• Relation of ARIES-I and PULSAR to the other ARIES designs
• Comparison of ARIES-I and PULSAR
• Some of the lessons learned from the studies
• Summary and conclusions
Comparison Chart between PULSAR and ARIES-I’

Physics assumptions of the two first stability devices are the same (except non-inductive current-drive physics).

<table>
<thead>
<tr>
<th></th>
<th>PULSAR</th>
<th>ARIES-I’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current-drive system</td>
<td>PF system very expensive, but efficient, separate system for heating</td>
<td>Non-inductive drive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expensive &amp; inefficient, used also for heating</td>
</tr>
<tr>
<td>Recirculating power</td>
<td>Low</td>
<td>High due to RF</td>
</tr>
<tr>
<td>Current Profile Control</td>
<td>No, 30%-40% bootstrap fraction ( \beta_N \sim 3, \beta \sim 2.8% )</td>
<td>Yes, 65%-75% bootstrap fraction ( \beta_N \sim 3.3, \beta \sim 1.9% )</td>
</tr>
<tr>
<td>Toroidal-field Strength</td>
<td>Lower because of interaction with cycling PF ( B \sim 14 \text{ T on coil} )</td>
<td>Higher ( B \sim 16 \text{ T on coil} )</td>
</tr>
<tr>
<td>Power Density</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Size and Cost</td>
<td>High (~ 9 m major radius)</td>
<td>Medium (~ 8 m major radius)</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>Yes, Shield</td>
<td>No need</td>
</tr>
<tr>
<td>Disruptions</td>
<td>More frequent</td>
<td>fewer</td>
</tr>
</tbody>
</table>

27 3/3/2005
Outline

• Overview of the ARIES studies
• Description of ARIES-I
• Description of PULSAR
• Relation of ARIES-I and PULSAR to the other ARIES designs
• Comparison of ARIES-I and PULSAR
• Some of the lessons learned from the studies
• Summary and conclusions
Many Critical Issues and dependencies have been uncovered by the ARIES Studies

**MHD Regime:**
- tradeoff $\beta$ for $I_{\text{BS}}/I_p$ (and alignment) and hence circulating power
- operate at 90% of $\beta$-limit to reduce disruption frequency
- severe constraints on close-fitting shell and $n>0$ feedback
- effect of ohmic-profiles on stable $\beta$ in non-CD machine
  - has implications for ITER

**Plasma Shaping:**
- plasma elongation limited by control-coil power and location
- plasma triangularity restricted by divertor geometry

**Current Drive:**
- need for efficient off-axis CD (other than LHCD)
- CD frequency also important for wall-plug efficiency
- minimize coverage of RF launchers to avoid affecting tritium breeding

**Divertors:**
- radiated power needed to reduce power to divertor
Outline

• Overview of the ARIES studies
• Description of ARIES-I
• Description of PULSAR
• Relation of ARIES-I and PULSAR to the other ARIES designs
• Comparison of ARIES-I and PULSAR
• Some of the lessons learned from the studies
• Summary and conclusions
Summary

• Both the ARIES-I and PULSAR designs are very close to the achieved physics data base
• Both steady-state and pulsed power plants tend to optimize at larger aspect ratio and low currents
• Even though the plasma $\beta$ is larger in a pulsed tokamak, the fusion power density (wall loading, etc) would be lower because the magnetic field at the coil would be lower
• A major innovation of the PULSAR study is the low-cost thermal storage system using the outboard shield
• The magnet system and fusion power core are much more complex in a pulsed-plasma tokamak, but there is no CD system
• Assuming the same availability and unit costs, PULSAR is about 25% more expensive than a comparable ARIES-I class device
• These designs provide an important backup if the more aggressive “Advanced Tokamak” designs prove impractical
<table>
<thead>
<tr>
<th>Date</th>
<th>Topic</th>
<th>Presenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>February 7</td>
<td>A Brief History of Fusion and Magnetic Fusion Basics</td>
<td>Meade</td>
</tr>
<tr>
<td>February 14</td>
<td>Recent JET Experiments and Science Issues</td>
<td>Strachan</td>
</tr>
<tr>
<td>February 21</td>
<td>Advanced Tokamaks FIRE to ARIES</td>
<td>Meade</td>
</tr>
<tr>
<td>February 28</td>
<td>The ARIES Power Plant Studies – Jardin</td>
<td>Jardin</td>
</tr>
<tr>
<td>March 7</td>
<td>IFE basics and NIF</td>
<td>Mark Herrmann(LLNL)</td>
</tr>
<tr>
<td></td>
<td>Midterms and Spring Break</td>
<td></td>
</tr>
<tr>
<td>March 21</td>
<td>The FESAC Fusion Energy Plan</td>
<td>Goldston</td>
</tr>
<tr>
<td>March 28</td>
<td>Fusion with High Power Lasers</td>
<td>Sethian(NRL)</td>
</tr>
<tr>
<td>April 4</td>
<td>ITER Physics and Technology</td>
<td>Sauthoff</td>
</tr>
<tr>
<td>April 11</td>
<td>Stellarator Physics and Technology</td>
<td>Zarnstorff</td>
</tr>
<tr>
<td>April 18</td>
<td>“New” Mirror Approaches for Fusion</td>
<td>Fisch</td>
</tr>
<tr>
<td>April 25</td>
<td>ST Science and Technology</td>
<td>Peng</td>
</tr>
<tr>
<td>May 2</td>
<td>FRC Science and Technology</td>
<td>Cohen</td>
</tr>
</tbody>
</table>
Lesson # 1:
It’s $\beta/\varepsilon$ (i.e. $\beta R_0/a$) that’s important, not $\beta$!

MHD Theory

1. Large aspect ratio expansion of MHD perturbed energy $\delta W$ shows that $\beta$ enters only as $\beta/\varepsilon$ (reduced MHD).

2. Troyon scaling may be written in dimensionless form as:

$$\beta/\varepsilon < C_T S/(20q^*)$$

Here, the right hand side is independent of $\varepsilon$. $C_T = 3.5$ is the Troyon coefficient, $q^* > 2$ is the cylindrical safety factor, and $S = (1+\kappa^2)/2$ is the shape factor.

SC Reactors

Power Density:

$$P \sim \beta^2 B_T^4 \varepsilon B_T^2$$

$$= (\beta/\varepsilon)^2 (\varepsilon B_T^2)^2$$

$\varepsilon = a/R$

$B_T = \mu_0 I_{TF}/2\pi R$
is limited by it’s value at the edge of the TF coil, $R \sim R_0 - 3a/2$
Lesson # 2:
Non-Inductive current drive is very costly!

\[
I_{CD} = \gamma_{CD} \left( \frac{P_{CD}}{n_e R} \right)
\]

- \( I_{CD} \) = Total non-inductively driven current (A)
- \( P_{CD} \) = Power to plasma by CD system (W)
- \( n_e \) = average density (in units of \( 10^{20}/m^3 \))
- \( R \) = major radius (m)
- \( \gamma_{CD} \) = CD figure of merit

- Theoretical calculations show \( \gamma_{CD} \propto T_e^n \) with \( 0.6 < n < 0.8 \)
- Highest values to date for \( \gamma_{CD} \) are 0.45 (JET with ICRF+LH) and 0.34 (JT-60 with LHCD). Note that for a Reactor with \( I_p=20 \) MA, \( n_e = 1.5 \times 10^{20} \), \( R = 8 \) m, \( \gamma_{CD} = 0.34 \), this gives
  \[
  P_{CD} = 700 \text{ MW to the plasma.}
  \]
- This is unrealistic for a 1000 MW Power plant, since wall plug power is much higher (several efficiencies involved)
- \( m \) most of the plasma current must be self-generated (bootstrap) for a non-inductive reactor