Historical Perspectives and Pathways to an Attractive Power Plant

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UC San Diego

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You can download a copy of the paper and the presentation from the ARIES Web Site:
ARIES Web Site: http://aries.ucsd.edu/ARIES/
The ARIES Team Has Examined Many Fusion Concepts As Power Plants

Focus of the talk is on Tokamak studies:

- ARIES-I first-stability tokamak (1990)
- ARIES-III D-\(^3\)He-fueled tokamak (1991)
- ARIES-II and -IV second-stability tokamaks (1992)
- Pulsar pulsed-plasma tokamak (1993)
- Starlite study (1995) (goals & technical requirements for power plants & Demo)
- ARIES-RS reversed-shear tokamak (1996)
- ARIES-AT advanced technology and advanced tokamak (2000)
ARIES Research Aims at a Balance Between Attractiveness & Feasibility

- **Top –Level Requirements for Commercial Fusion Power**
  - Have an economically competitive life-cycle cost of electricity:
    - Low recirculating power;
    - High power density;
    - High thermal conversion efficiency;
    - Less-expensive systems.
  - Gain Public acceptance by having excellent safety and environmental characteristics:
    - Use low-activation and low toxicity materials and care in design.
  - Have operational reliability and high availability:
    - Ease of maintenance, design margins, and extensive R&D.

**Reasonable Extension of Present Data base**
- **Physics**: Solid Theoretical grounds and/or experimental basis.
- **Technology**: Demonstrated at least in small samples.
Power Plant Physics Needs and Directions for Burning Plasma Experiments
For the same physics and technology basis, steady-state devices outperform pulsed tokamaks.

- Physics needs of pulsed and steady-state first stability devices are the same (except non-inductive current-drive physics).

<table>
<thead>
<tr>
<th></th>
<th>Pulsar</th>
<th>ARIES-I’</th>
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</thead>
<tbody>
<tr>
<td>Current-drive system</td>
<td>PF System</td>
<td>Non-inductive drive</td>
</tr>
<tr>
<td></td>
<td>Very expensive but efficient</td>
<td>Expensive &amp; inefficient</td>
</tr>
<tr>
<td>Recirculating Power</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Current profile Control</td>
<td>No, 30%-40% bootstrap fraction, $\beta_N \sim 3$, $\beta \sim 2.1%$</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 PF (B $\sim 14$ T on coil)</td>
<td>Higher (B $\sim 16$ 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>
</tbody>
</table>
**Directions for Improvement**

**Increase Power Density (1/Vp)**
- What we pay for, $V_{\text{FPC}}$
- Improvement "saturates" at ~5 MW/m² peak wall loading (for a 1GWe plant).
- A steady-state, first stability device with Nb₃Sn technology has a power density about 1/3 of this goal.

**Decrease Recirculating Power Fraction**
- Improvement "saturates" about $Q \sim 40$.
- A steady-state, first stability device with Nb₃Sn Tech. has a recirculating fraction about 1/2 of this goal.

**High-Field Magnets**
- ARIES-I with 19 T at the coil (cryogenic).
- Advanced SSTR-2 with 21 T at the coil (HTS).

**High bootstrap, High $\beta$**
- 2nd Stability: ARIES-II/IV
- Reverse-shear: ARIES-RS, ARIES-AT, A-SSRT2
Reverse Shear Plasmas Lead to Attractive Tokamak power Plants

**Second Stability Regime**

- Requires wall stabilization (Resistive-wall modes)
- Poor match between bootstrap and equilibrium current profile at high $\beta$.
- **ARIES-II/IV**: Optimum profiles give same $\beta$ as first-stability but with increased bootstrap fraction

**Reverse Shear Regime**

- Requires wall stabilization (Resistive-wall modes)
- Excellent match between bootstrap & equilibrium current profile at high $\beta$.
- **ARIES-RS** (medium extrapolation): $\beta_N = 4.8$, $\beta = 5\%$, $P_{cd} = 81$ MW (achieves $\sim 5$ MW/m$^2$ peak wall loading.)
- **ARIES-AT** (aggressive extrapolation): $\beta_N = 5.4$, $\beta = 9\%$, $P_{cd} = 36$ MW (high $\beta$ is used to reduce peak field at magnet)
# Evolution of ARIES Tokamak Designs

<table>
<thead>
<tr>
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<th>1st Stability, Nb₃Sn Tech.</th>
<th>High-Field Option</th>
<th>Reverse Shear Option</th>
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<tr>
<td></td>
<td>ARIES-I’</td>
<td>ARIES-I</td>
<td>ARIES-RS</td>
</tr>
<tr>
<td>Major radius (m)</td>
<td>8.0</td>
<td>6.75</td>
<td>5.5</td>
</tr>
<tr>
<td>$\beta$ ($\beta_N$)</td>
<td>2% (2.9)</td>
<td>2% (3.0)</td>
<td>5% (4.8)</td>
</tr>
<tr>
<td>Peak field (T)</td>
<td>16</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Avg. Wall Load (MW/m²)</td>
<td>1.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
<td>Current-driver power (MW)</td>
<td>237</td>
<td>202</td>
<td>81</td>
</tr>
<tr>
<td>Recirculating Power Fraction</td>
<td>0.29</td>
<td>0.28</td>
<td>0.17</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td>0.46</td>
<td>0.49</td>
<td>0.46</td>
</tr>
<tr>
<td>Cost of Electricity (c/kWh)</td>
<td>10</td>
<td>8.2</td>
<td>7.5</td>
</tr>
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</table>

- COE insensitive of power density
- COE insensitive of current drive
Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology

- **Major radius (m)**
  - Mid 80's Pulsar
  - Early 90's ARIES-I
  - Late 90's ARIES-RS
  - 2000 ARIES-AT

- **Estimated Cost of Electricity (1992 c/kWh)**
  - Mid 80's Physics
  - Early 90's Physics
  - Late 90's Physics
  - Advanced Technology

Approaching COE insensitive of power density

High Thermal Efficiency
High $\beta$ is used to lower magnetic field
Continuity of ARIES Research Has Led to the Progressive Refinement of Plasma Optimization

<table>
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<tr>
<th>Pulsar (pulsed-tokamak):</th>
<th>For the same physics &amp; technology basis, steady-state operation is better</th>
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<tr>
<td>• Trade-off of $\beta$ with bootstrap</td>
<td>Need high $\beta$ equilibria with aligned bootstrap</td>
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<td>• Expensive PF system, under-performing TF</td>
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<th>ARIES-I (first-stability steady-state):</th>
<th>Improved Physics</th>
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<tr>
<td>• Trade-off of $\beta$ with bootstrap</td>
<td>Better bootstrap alignment</td>
</tr>
<tr>
<td>• High-field magnets to compensate for low $\beta$</td>
<td>More detailed physics</td>
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<th>ARIES-RS (reverse shear):</th>
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<td>• Improvement in $\beta$ and current-drive power</td>
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<td>• Approaching COE insensitive of current drive</td>
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<th>ARIES-AT (aggressive reverse shear):</th>
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<td>• Approaching COE insensitive of power density</td>
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<tr>
<td>• High $\beta$ is used to reduce toroidal field</td>
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There has been substantial changes in our predications of edge plasma properties.

**Pulsar (pulsed-tokamak):**
- Trade-off of $\beta$ with bootstrap
- Expensive PF system, under-performing TF

**ARIES-I (first-stability steady-state):**
- Trade-off of $\beta$ with bootstrap
- High-field magnets to compensate for low $\beta$

**ARIES-RS (reverse shear):**
- Improvement in $\beta$ and current-drive power
- Approaching COE insensitive of current drive

**ARIES-AT (aggressive reverse shear):**
- Approaching COE insensitive of power density
- High $\beta$ is used to reduce toroidal field

- (1900-1993) L-mode edge, high-recycling divertor,
- 5MW/m$^2$ peak heat load
- He-cooled with W armor

- (1996) L-mode edge, Detached
- 5MW/m$^2$ peak heat load
- He-cooled with W armor

- (1999) H-mode edge, high radiation in core and edge plasma
- 5MW/m$^2$ peak heat load
- PbLi-cooled with W armor
There has been substantial changes in our predictions of edge plasma properties

- Current expectation of much higher peak heat and particle flux on divertors:
  - Scrape-off layer energy e-folding length is substantially smaller.
  - Elms and intermittent transport
- Gad-cooled W divertor designs with capability of 10-12MW/m² has been produced.
- More work is needed to quantify the impact of the new physics predictions on power plant concepts.

ARIES-CS T-Tube concept
Continuity of ARIES Research Has Led to the Progressive Refinement of Plasma Optimization

**Pulsar (pulsed-tokamak):**
- Trade-off of $\beta$ with bootstrap
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- Improvement in $\beta$ and current-drive power
- Approaching COE insensitive of current drive

**ARIES-AT (aggressive reverse shear):**
- Approaching COE insensitive of power density
- High $\beta$ is used to reduce toroidal field

“Conventional” Pulsed plasma:
Explore burn physics (ITER)

Demonstrate steady-state first-stability operation. (ITER)

Explore reversed-shear plasma
a) Higher Q plasmas
b) At steady state

Explore envelopes of steady-state reversed-shear operation
Fusion Technologies Have a Dramatic Impact on the Attractiveness of Fusion
SiC composites are attractive structural material for fusion

- Excellent safety & environmental characteristics (very low activation and very low afterheat).
- High performance due to high strength at high temperatures (>1000°C).
- Large world-wide program in SiC:
  - New SiC composite fibers with proper stoichiometry and small O content.
  - New manufacturing techniques based on polymer infiltration or CVI result in much improved performance and cheaper components.
  - Recent results show composite thermal conductivity (under irradiation) close to 15 W/mK which was used for ARIES-I.
Continuity of ARIES research has led to the progressive refinement of research

**ARIES-I:**
- SiC composite with solid breeders
- Advanced Rankine cycle

**Starlite & ARIES-RS:**
- Li-cooled vanadium
- Insulating coating

**ARIES-ST:**
- Dual-cooled ferritic steel with SiC inserts
- Advanced Brayton Cycle at $\geq 650$ °C

**ARIES-AT:**
- LiPb-cooled SiC composite
- Advanced Brayton cycle with $\eta = 59\%$

Many issues with solid breeders; Rankine cycle efficiency saturated at high temperature

Max. coolant temperature limited by maximum structure temperature

High efficiency with Brayton cycle at high temperature
ARIES-AT features a high-performance blanket

- Simple, low pressure design with SiC structure and LiPb coolant and breeder.
- Innovative design leads to high LiPb outlet temperature (~1,100°C) while keeping SiC structure temperature below 1,000°C leading to a high thermal efficiency of ~ 60%.
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
Design leads to a LiPb Outlet Temperature of 1,100°C While Keeping SiC Temperature Below 1,000°C

- Two-pass PbLi flow, first pass to cool SiCf/SiC box second pass to superheat PbLi

![Diagram showing temperature distribution and flow paths with key points:
- PbLi Inlet Temp. = 764°C
- Max. SiC/SiC Temp. = 996°C
- Max. SiC/PbLi Interf. Temp. = 994°C
- PbLi Outlet Temp. = 1100°C]
Modular sector maintenance enables high availability

- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks
After 100 years, only 10,000 Curies of radioactivity remain in the 585 tonne ARIES-RS fusion core.

SiC composites lead to a very low activation and afterheat.

All components of ARIES-AT qualify for Class-C disposal under NRC and Fetter Limits. 90% of components qualify for Class-A waste.

Radioactivity levels in fusion power plants are very low and decay rapidly after shutdown.
Fusion Core Is Segmented to Minimize the Rad-Waste

Blanket 1 (replaceable)
Blanket 2 (lifetime)
Shield (lifetime)

➢ Only “blanket-1” and divertors are replaced every 5 years
Waste volume is not large

- 1270 m³ of Waste is generated after 40 full-power year (FPY) of operation.
  - Coolant is reused in other power plants
  - 29 m³ every 4 years (component replacement), 993 m³ at end of service
- Equivalent to ~ 30 m³ of waste per FPY
  - Effective annual waste can be reduced by increasing plant service life.

90% of waste qualifies for Class A disposal.
Some thoughts on Fusion Development
Fusion Development Focuses on Facilities Rather than the Path

- Current fusion development plans relies on large scale, expensive facilities.
- This is partly due to our history: To study a fusion plasma, we need to create it, thus a larger facility.
- This is NOT true for the development of fusion engineering and leads to an expensive and long development path
  - long lead times, $$$
  - Expensive operation time
  - Limited no. concepts that can be tested
  - Integrated tests either succeed or fail, this is an expensive and time-consuming approach to optimize concepts.
- It is argued that facilities provide a focal point to do the R&D. This is in contrast with the normal development path of any product in which the status of R&D necessitates a facility for experimentation.
Technical Readiness Levels provides a basis for development path analysis

- TRLs are a set of 9 levels for assessing the maturity of a technology (level 1: “Basis principles observed” to level 9: “Total system used successfully in project operations”).
- Developed by NASA and are adopted by US DOD and DOE.
- Provides a framework for assessing a development strategy.

- Initial application of TRLs to fusion system clearly underlines the relative immaturity of fusion technologies compared to plasma physics.
- TRLs are very helpful in defining R&D steps and facilities.
## Example: TRLs for Plasma Facing Components

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<th>Facilities</th>
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<td>System studies to define tradeoffs and requirements on heat flux level, particle flux level, effects on PFC's (temperature, mass transfer).</td>
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<td>Larger-scale facilities for submodule testing, High-temperature + all expected range of conditions</td>
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<tr>
<td>5</td>
<td>Integrated module testing of the PFC concept in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.</td>
<td>Integrated large facility: Prototypical plasma particle flux+heat flux <em>(e.g. an upgraded DIII-D/JET?)</em></td>
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<td>Prototypic PFC system demonstration in a fusion machine.</td>
<td>Fusion machine</td>
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<td>Actual PFC system demonstration qualification in a fusion machine over long operating times.</td>
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<td>9</td>
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- **Power-plant relevant high-temperature gas-cooled PFC**
- **Low-temperature water-cooled PFC**
We should Focus on Developing a Comprehensive Fusion Development Path

- Use modern approaches for to “product development;” (e.g., science-based engineering development vs “cook and look”)
  - Extensive “out-of-pile” testing to understand fundamental processes
  - Extensive use of simulation techniques to explore many of synergetic effects and define new experiments
  - Lessons from industry (e.g., defense, aerospace)

- Final integration facility should focus on validation and demonstration rather than experimentation
CTF should focus on validation and demonstration rather than experimentation

- **Demo**: Build and operated by industry (may be with government subsidy), Demo should demonstrate that fusion is a commercial reality (different than EU definition)
  - There should be NO open questions going from Demo to commercial (similar physics and technology, …)

- **CTF**: Integration of fusion nuclear technology with a fusion plasma (copious amount of fusion power but not necessarily a burning plasma).
  At the of its program, CTF should have demonstrated:
  - Complete fuel cycle with tritium accountability.
  - Power and particle management.
  - Necessary date for safety & licensing of a fusion facility.
  - Operability of a fusion energy facility, including plasma control, reliability of components, inspectability and maintainability of a power plant relevant device.
  - Large industrial involvement so that industry can attempt the Demo.
Can we develop fusion rapidly?

Issues:
- expertise (scientific workforce)
- Test facilities (small and Medium scale)
- Industrial involvement
- Funding

Considering the current state of Fusion Engineering, we need 5-10 years of program growth before the elements of a balanced program are in place and we are ready to field a CTF.

Such a science-based engineering approach, will provide the data base and expertise needed to field a successful CTF in parallel to ITER ignition campaign and can lead to fielding a fusion Demo within 20-25 years.
Thank you!