Contributions of Burning Plasma Physics Experiment to Fusion Energy Goals

Farrokh Najmabadi
Dept. of Electrical & Computer Eng. And Center for Energy Research
University of California, San Diego,

Burning Plasma Science Workshop II
May 1-2, 2001
General Atomics, San Diego, CA

You can download a copy of the paper and the presentation from the ARIES Web Site:
ARIES Web Site: http://aries.ucsd.edu/PUBLIC
Translation of Requirements to GOALS for Fusion Power Plants

- **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.

- **Acceptable cost of development.**
Main Contribution of a Burning Plasma Experiment Is to Identify and Demonstrate Optimum Plasma Regime of Operation for Power Plants

- The key is predictive capability!

- A single machine can only explore a region of operation space:
  * Use existing knowledge and power plant studies to identify the most promising design space.

- The collection of ARIES designs form a good basis for experimental plans and progress in a Burning Plasma experiment.

- Focus of talk and optimizations is ~1000-MWe power plants.
  * For a certain regime of operation, a power plant, a burning plasma experiment, and a confinement experiment each optimize in a different set of global parameters (e.g., $A$, $R$, …). Focus should be on the regime of operation!
Optimization of Power Plant Plasmas—First, We Need to Make Fusion Power!

Confinement Time and Transport

- Typically, global confinement is not a major issue in a power plant. All ARIES designs require confinement performance similar to present experiments: H(89P) ~2-3. A better confinement has to be degraded!

- For a burning plasma experiments, good global confinement means we can built a smaller (fusion power) machine. After the machine is operational, confinement better than needed for ignition has to be degraded!
  
  * A Burning Plasma Experiment should show that a steady fusion burn can be achieved (power and particle control) and fusion power can be controlled within a few percent of its nominal value.
  
  * Understanding (and manipulating) local transport is critical to optimizing plasma profiles.
Next, We Need to Make Electric Power!

Recirculating Power Should Be Low! Steady-state or Pulsed operation?

- A good comparison: Pulsar pulsed-plasma and ARIES-I first-stability, steady-state.

- **Perception:** The drawback of pulsed-plasma operation is pulsed output power. *(Incorrect)*
  
  * Pulsar design included an innovative energy storage system that allowed pulsed-plasma operation while keeping the plant thermal output steady.

- **Perception:** Pulsed-plasma operation does not need any current-drive system. There is more flexibility in choosing plasma parameters. *(Incorrect)*
  
  * Pulsed operation has a current-drive system, the PF system. This “current-drive” system is quite expensive (large volt-sec and rapid current ramp). PF system of Pulsar is about 4 times more expensive than ARIES-I.
  * Because the inductive drive system is expensive, one needs to maximize bootstrap fraction and operate with maximum drive efficiency (high temperature, low impurity concentration, etc.)

⇒ Physics needs of pulsed and steady-state first stability devices are the same (except non-inductive current-drive physics). Both need to trade-off $\beta$ with bootstrap!
Optimization of Power Plant Plasmas—Steady-state or Pulsed operation?

- Pulsed-operation: $n$ and $T$ profiles uniquely determine pressure and current density profile (loop voltage is constant across plasma cross section). Optimum regime is $\beta_N \sim 3$ and bootstrap fraction 30% to 40%.

- Steady-state operation: Current density profile can be tailored: $\beta_N \sim 3.4$ and bootstrap fraction 60% to 75%.

- Higher field in the PF system (larger $V_s$) and rapid current ramp in a pulsed-plasma system leads to a lower toroidal field strength compared to a steady-state device for the same magnet technology (same conductor and structural material).
  
  * For the same magnet technology, the steady-state device has a higher fusion power density, it is smaller and cheaper.

- For the same physics and technology basis, a steady-state first-stability device outperforms a pulsed-plasma tokamak.

- Steady-state first-stability operation, entry level to advanced tokamak modes, leads to an acceptable fusion power plant. It should be demonstrated in a burning-plasma experiment.
Optimization of Power Plant Plasmas—Next, Increase Power Density

• Cost of fusion plant decreases with increased power density. For a 1GWe plant, this improvement “saturates” at ~5 MW/m² peak wall loading.

- A steady-state, first stability device with Nb₃Sn magnet technology has a power density about 1/2 of this goal. Two options are possible:

  ✓ Develop high-field magnets:
    * ARIES-I pushed the limit for cryogenic superconductor to 19T (1990).
    * Advanced STTR-2 proposes high-temperature superconductor to achieve 21 T (2000).

  ✓ High-bootstrap plasma with higher $\beta \Rightarrow$ Reversed shear plasma
    * Added benefit of higher bootstrap fraction,
    * Resistive wall modes should be stabilized.
    * ARIES-RS (medium extrapolation): $\beta_N = 4.8$, $\beta=5\%$, $P_{cd}=81$ MW (achieves ~5 MW/m² peak wall loading.)
    * ARIES-AT (Aggressive): $\beta_N = 5.4$, $\beta=9\%$, $P_{cd}=36$ MW (high $\beta$ is used to reduce peak field at magnet)
Continuity of ARIES Research Has Led to the Progressive Refinement of Plasma Optimization

**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 power density

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

For the same physics & technology basis, steady-state operation is better

Need high $\beta$ equilibria with aligned bootstrap

Better bootstrap alignment
More detailed physics
Our Vision of Magnetic Fusion Power Systems Has Improved Dramatically in the Last Decade, and Is Directly Tied to Advances in Fusion Science & Technology

Estimated Cost of Electricity (c/kWh)

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Estimated Cost of Electricity (c/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid 80's Physics</td>
<td>14</td>
</tr>
<tr>
<td>Early 90's Physics</td>
<td>12</td>
</tr>
<tr>
<td>Late 90's Physics</td>
<td>10</td>
</tr>
<tr>
<td>Advanced Technology</td>
<td>8</td>
</tr>
</tbody>
</table>

Major radius (m)

<table>
<thead>
<tr>
<th>System</th>
<th>Major radius (m)</th>
<th>Fusion Power</th>
<th>Net Electric</th>
<th>COE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid 80's Pulsar</td>
<td>9.2 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Early 90's ARIES-I</td>
<td>8.6 m</td>
<td>1,760 MW</td>
<td>1,000 MW</td>
<td></td>
</tr>
<tr>
<td>Late 90's ARIES-RS</td>
<td>7.8 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000 ARIES-AT</td>
<td>6.0 m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ARIES-AT parameters:

- Major radius: 5.2 m
- Toroidal $\beta$: 9.2%
- Avg. Wall Loading: 3.3 MW/m²
- Fusion Power: 1,760 MW
- Net Electric: 1,000 MW
- COE: 4.7 c/kWh
ARIES designs Correspond to Experimental Progress in a Burning Plasma Experiment

**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 power density

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

“Conventional” Pulsed plasma: Explore burn physics

Demonstrate steady-state first-stability operation.

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

Explore envelopes of steady-state reversed-shear operation

Improved Physics
Perception: The best solution is use a radiative mantel to distribute the heat on the first wall uniformly because this leads to lowest heat flux. (Incorrect)

* It is typically easier to cool a divertor plate at 5 MW/m² than the inboard first wall at 1 MW/m² (because of coolant flow path is longer and space is more limited).
* H-mode edge requires a radiative mantel and does not lead to the best power and particle control solution (too high a heat flux on the first wall, too much impurities).
* L-mode edge is much preferred for power and particle control (combined with high-recycling or detached divertor).
* Current tokamak experiments can make considerable progress in this area.
Main contribution of a burning plasma experiment is to identify and demonstrate optimum plasma regime of operation for power plants.

* Pulsed-plasma operations to explore burn physics.
* Demonstration of first-stability, steady-state operation as an entry to advanced tokamak modes and an acceptable fusion power plant.
* Exploration of reversed shear mode for study of higher Q plasma at steady state.
* Exploration of envelopes of reversed-shear regime.

Capability to perform technology testing probably adds considerably to the cost of a burning plasma experiment. It is probably more cost-effective to develop fusion technologies separately and test them in a high-fluence follow-up device to the burning-plasma experiment.

* But we need to do technology development now to be ready for such a follow-up device.