The Future Prospects of Fusion Power Plants

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Why Should We Develop Fusion?

- We are running out of energy resources, there is a need for inexhaustible energy source:
  - But energy sources are plentiful!
  - The issue is distribution of energy resources (i.e., fossil fuel).
- Each Energy Source has one or more supply, cost, and social/environmental issue. Fusion has the potential to address all these issues:
  - But, historically speaking, technology development has proved deft at addressing such issues.
  - These concerns are correlated to “popular” vision of danger/benefit (as opposed to a scientific correlation);
  - Ratio of R&D to sales in energy technologies is lowest among all technologies. Public expenditures in energy technologies are very high due to subsidies!
- We need to deploy non-Carbon emitting technologies because of Climate Change:
  - The climate driven need for new technology will be largest (2nd half of 21st century) when fusion is most likely to become available.
  - But, there are lots of options. If a technology cannot deliver on cost, performance, other environmental concerns, health, and safety issues, its competitors will.
Why Should We Develop Fusion?

- **My Observations:**
  
  ✓ There is no conclusive argument that fusion is absolutely necessary. There are a lot of arguments that it can be a big part of portfolio of energy technologies.

  ✓ In all cases, fusion has to compete with a range of energy options. **It has to deliver on cost, social/environmental concerns, and technical viability as a commercial energy source.**

  ✓ This presentation argues that potential fusion embodiments and technologies exists to deliver the full potential of fusion.

  ✓ Are current R&D priorities aimed at developing full potential of fusion in an efficient manner (cheapest & fastest)?
Work reported here are from ARIES national fusion power plant studies program.

More info is available at: http://aries.ucsd.edu/

1) University of California, San Diego,
2) Boeing High Energy Systems,
3) General Atomics,
4) Idaho National Laboratory
5) Massachusetts Institute of Technology
6) Princeton Plasma Physics Laboratory
7) Rensselaer Polytechnic Institute
8) University of Wisconsin - Madison
9) Forschungszentrum Karlsruhe
Framework of ARIES Studies: Assessment Based on Attractiveness & Feasibility

Periodic Input from Energy Industry → Goals and Requirements

Scientific & Technical Achievements

Projections and Design Options

Evaluation Based on Customer Attributes Attractiveness

Characterization of Critical Issues Feasibility

Balanced Assessment of Attractiveness & Feasibility

R&D Needs and Development Plan

No: Redesign

Yes
Elements of the Case for Fusion Power Were Developed through Interaction with Representatives of U.S. Electric Utilities and Energy Industry

- Have an economically competitive life-cycle cost of electricity
- Gain Public acceptance by having excellent safety and environmental characteristics
  - No disturbance of public’s day-to-day activities
  - No local or global atmospheric impact
  - No need for evacuation plan
  - No high-level waste
  - Ease of licensing
- Reliable, available, and stable as an electrical power source
  - Have operational reliability and high availability
  - Closed, on-site fuel cycle
  - High fuel availability
  - Capable of partial load operation
  - Available in a range of unit sizes

Low-activation material
Framework of ARIES Studies: Assessment Based on Attractiveness & Feasibility

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Characterization of Critical Issues: Feasibility

Balanced Assessment of Attractiveness & Feasibility

R&D Needs and Development Plan

Yes

No: Redesign
Portfolio of MFE Configurations

Externally Controlled

Example: Stellarator
Confinement field generated by mainly external coils
Toroidal field >> Poloidal field
Large aspect ratio
More stable, better confinement

Self Organized

Example: Field-reversed Configuration
Confinement field generated mainly by currents in the plasma
Poloidal field >> Toroidal field
Small aspect ratio
Simpler geometry, higher power density
Portfolio of IFE Configurations

Driver:

- Lasers
  \( (\eta = 5\%-10\%) \)
- Heavy-ions
  \( (\eta = 15\%-40\%) \)
- Z-pinch
  \( (\eta \sim 15\%) \)

Target:

- Direct drive
  \( \eta G > 10 \) for energy
- Indirect drive

Chamber:

- Dry Walls
- Liquid Walls: HYLIFE II
ARIES-AT is an attractive vision for fusion with a reasonable extrapolation in physics & technology

- Competitive cost of electricity (5c/kWh);
- Steady-state operation;
- Low level waste;
- Public & worker safety;
- High availability.
A dramatic change occurred in 1990: Introduction of Advanced Tokamak

- Our vision of a fusion system in 1980s was a large pulsed device.
  - Non-inductive current drive is inefficient.
- Some important achievements in 1980s:
  - Experimental demonstration of bootstrap current;
  - Development of ideal MHD codes that agreed with experimental results.
  - Development of steady-state power plant concepts (ARIES-I and SSTR) based on the trade-off of bootstrap current fraction and plasma $\beta$

ARIES-I: $\beta_N = 2.9$, $\beta = 2\%$, $P_{cd} = 230$ MW

Reverse Shear Regime

- 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 $\approx 5$ 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)
DT Fusion requires a T breeding blanket

**Requirement:** Plasma should be surrounded by a blanket containing Li

\[
\begin{align*}
D + T &\rightarrow He + n \\
n + ^6Li &\rightarrow T + He
\end{align*}
\]

\[
D + ^6Li \rightarrow He + He
\]

- DT fusion turns its waste (neutrons) into fuel!
- Through careful design, only a small fraction of neutrons are absorbed in structure and induce radioactivity
  - Rad-waste depends on the choice of material: Low-activation material
  - Rad-waste generated in DT fusion is similar to advanced fuels (D-3He)
  - For liquid coolant/breeders (e.g., Li, LiPb), most of fusion energy (carried by neutrons) is directly deposited in the coolant simplifying energy recovery

**Issue:** Large flux of neutrons through the first wall and blanket:
- Need to develop radiation-resistant, low-activation material:
  - Ferritic steels, Vanadium alloys, SiC composites
Framework of ARIES Studies:
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- Characterization of Critical Issues
  - Feasibility
- Balanced Assessment of Attractiveness & Feasibility
  - No: Redesign
  - Yes: R&D Needs and Development Plan
## Evolution of ARIES Designs

<table>
<thead>
<tr>
<th></th>
<th>1st Stability, Nb₃Sn Tech.</th>
<th>High-Field Option</th>
<th>Reverse Shear Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARIES-IA</td>
<td>ARIES-I</td>
<td>ARIES-RS</td>
<td>ARIES-AT</td>
</tr>
<tr>
<td>Major radius (m)</td>
<td>8.0</td>
<td>6.75</td>
<td>5.5</td>
</tr>
<tr>
<td>β (βₙ)</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>
</tbody>
</table>

Approaching COE insensitive of power density
Directions for Improvement

**Increase Power Density**

- Big Win: \( r > \Delta \)
- Little Gain: \( r \sim \Delta \)
- Little Gain: \( r < \Delta \)

- Improvement “saturates” at \( \sim 5 \text{ MW/m}^2 \) peak wall loading (for a 1GWe plant).

- A steady-state, first stability device with Nb\(_3\)Sn 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 Nb\(_3\)Sn 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 \( \beta \)**

- ✓ 2\(^{nd}\) Stability: ARIES-II/IV
- ✓ Reverse-shear: ARIES-RS, ARIES-AT, A-SSRT2
There Is Little Economic Benefit for Operating Beyond 5-10 MW/m² of Wall Load

- ARIES-RS, ARIES-ST, and ARIES-AT have not optimized at the highest wall load (all operate at around 5 MW/m² peak)

- Physics & Engineering constraints cause departure from geometrical dependence e.g., high field needed for high load increases TF cost

- ARIES-AT optimizes at lower wall loading because of high efficiency.
There Is Little Economic Benefit for Operating Beyond ~5 MW/m² of Wall Load

COE is reduced for smaller devices
There Is Little Economic Benefit for Operating Beyond ~5 MW/m² of Wall Load

Advanced Technology has a dramatic impact!
ARIES-I Introduced SiC Composites as A High-Performance 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 $\geq 650 \, ^\circ C$

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
Advanced Brayton Cycle Parameters Based on Present or Near Term Technology Evolved with Expert Input from General Atomics*

Key improvement is the development of cheap, high-efficiency recuperators.
ARIES-ST Featured a High-Performance Ferritic Steel Blanket

- Originally developed for ARIES-ST, further developed by EU (FZK).
- Typically, the coolant outlet temperature is limited to the max. operating temperature of structural material (550°C for ferritic steels).
- A coolant outlet temperature of 700°C is achieved by using a coolant/breeder (LiPb), cooling the structure by He gas, and SiC insulator lining PbLi channel for thermal and electrical insulation.
ARIES-AT: SiC Composite Blankets

- 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.
Innovative Design Results in a LiPb Outlet Temperature of $1,100^\circ$C While Keeping SiC Temperature Below $1,000^\circ$C

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

![Diagram showing PbLi temperature distribution and heat transfer](image)

- PbLi Inlet Temp. = $764^\circ$C
- Max. SiC/SiC Temp. = $996^\circ$C
- Max. SiC/PbLi Interf. Temp. = $994^\circ$C

- PbLi Outlet Temp. = $1100^\circ$C
Fusion core cost fraction should be reduced

Total Capital Cost ($k)

ARIES-AT                 ARIES-RS        ARIES-I (19T)            ARIES-I (16T)               Fission

Fusion Core Cost

Total Direct Cost

Fusion Core Cost

Total Direct Cost

ARIES-AT

ARIES-RS

ARIES-I (19T)

ARIES-I (16T)

Fission

32%                         45%                         54%                     57%                      10%-15%
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- Characterization of Critical Issues
  - Feasibility
- R&D Needs and Development Plan

No: Redesign
Yes
ARIES-AT is Competitive with Other Future Energy Sources

Estimated range of COE (c/kWh) for 2020*

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>COE Range (c/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>2-6</td>
</tr>
<tr>
<td>Coal</td>
<td>5-6</td>
</tr>
<tr>
<td>Nuclear</td>
<td>4-6</td>
</tr>
<tr>
<td>Wind (Intermittent)</td>
<td>3-5</td>
</tr>
<tr>
<td>Fusion (ARIES-AT)</td>
<td>1-2</td>
</tr>
</tbody>
</table>

AT 1000 (1 GWe)
AT 1500 (1.5 GWe)

EPRI Electric Supply Roadmap (1/99):
- Blue: Business as usual
- Red: Impact of $100/ton Carbon Tax.

* Data from Snowmass Energy Working Group Summary. (2025 COE, 2003$)

Estimates from Energy Information Agency:
Some Data from US Energy Information Agency Annual Energy Outlook 2005

**Figure 1. Energy prices, 1970-2025 (2003 dollars per million Btu)**

**Figure 5. Electricity generation by fuel, 1970-2025 (billion kilowatthours)**

**Figure 8. Projected U.S. carbon dioxide emissions by sector and fuel, 1990-2025 (million metric tons)**
Radioactivity Levels in Fusion Power Plants Are Very Low and Decay Rapidly after Shutdown

- 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.

After 100 years, only 10,000 Curies of radioactivity remain in the 585 tonne ARIES-RS fusion core.
Fusion Core Is Segmented to Minimize the Rad-Waste

- Only “blanket-1” and divertors are replaced every 5 years

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

➢ Only “blanket-1” and divertors are replaced every 5 years
Generated radioactivity waste is reasonable

- 1270 m³ of Waste is generated after 40 full-power year (FPY) of operation (~50 years)
  - 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

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![Graph showing cumulative compacted waste volume for different components: Blanket, Shield, Vacuum Vessel, Magnets, Structure, Cryostat.](image1)

![Graph showing cumulative compacted waste volume for Class A and Class C disposal.](image2)
Advances in plasma physics has led to a dramatic improvement in our vision of fusion systems

- Attractive visions for tokamak exist.
- The main question is to what extent the advanced tokamak modes can be achieved in a burning plasma (e.g., ITER):
  - What is the achievable $\beta_N$ (macroscopic stability)
  - Can the necessary pressure profiles realized in the presence of strong $\alpha$ heating (microturbulence & transport)
- Attractive visions for ST and stellarator configurations also exist

- Advanced Technologies have a large impact on fusion competitiveness.
- Pace of “Technology” research, however, has been considerably slower than progress in plasma physics and much less ambitious!