Magnetic Fusion Power Plants

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EPRI,
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Conceptual designs studies of fusion power plants are performed by the ARIES national team

- National ARIES Team comprises key members from major fusion centers (universities, national laboratories, and industry).
- Many studies of evolving confinement concepts and different technologies.
Framework: 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

Yes
- R&D Needs and Development Plan

No:
- Redesign
Utility/industrial advisory committees have defined customer requirements

- Fusion Power Plant Studies Utility Advisory Committee and EPRI Fusion Working Group*
  - Chaired by Steve Rosen & Jack Kaslow respectively,
  - Helped define goals and top-level requirements.
  - Had a major impact on safety/licensing as well as configuration/maintenance approach.

- Input as members of review committee for individual designs.

* See http://aries.ucsd.edu/ARIES/DOCS/UAC/ for membership and meeting minutes.
Goals & Top-Level Requirements for Fusion Power Plants Were Developed in Consultation with US 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
  - Low-activation material

- Reliable, available, and stable as an electrical power source
  - Have operational reliability and high availability
  - Closed, on-site fuel cycle
  - High fuel availability
  - Available in a range of unit sizes

Fusion Fuel Cycle
Framework: 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

No: Redesign
Yes
Detailed analyses are necessary to understand trade-offs

Plasma analysis

Engineering Design

System Analysis and Trade-offs

Self-consistent point design for a fusion power plant
Detailed analyses are necessary to understand trade-offs

Plasma analysis
- High accuracy equilibria;
- Large ideal MHD database over profiles, shape and aspect ratio;
- RWM stable with wall/rotation or wall/feedback control;
- NTM stable with LHCD;
- Bootstrap current consistency using advanced bootstrap models;
- External current drive;
- Vertically stable and controllable with modest power (reactive);
- Rough kinetic profile consistency with RS/ITB experiments, as well GLF23 transport code;
- Modest core radiation with radiative SOL/divertor;
- Accessible fueling;
- No ripple losses;
- 0-D consistent startup;

Engineering Design
- Superconducting magnet design
- First wall/blanket, and shield, Divertor;
- Current-drive systems (Launchers, transmission lines, sources) ;
  - Configuration
  - Neutronics & Shielding
  - Thermo-fluid & thermo mechanical design
  - MHD effects
  - Tritium Breeding & management
  - Erosion
  - Off-normal events
  - Inventory

- Waste Disposal
- Safety Analysis
- Maintenance
DT Fusion requires a tritium-breeding blanket

Plasma should be surrounded by a blanket containing Li

\[
\begin{align*}
D + T & \rightarrow ^4\text{He} \ (3.5 \ \text{MeV}) + n \ (14 \ \text{MeV}) \\
n + ^6\text{Li} & \rightarrow ^4\text{He} \ (2 \ \text{MeV}) + T \ (2.7 \ \text{MeV})
\end{align*}
\]

- Through care in 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
  - For liquid coolant/breeders (e.g., Li, LiPb), most of fusion energy (carried by neutrons and n-Li reaction) is directly deposited in the coolant simplifying energy recovery

- Issue: Large flux of high-energy neutrons through the first wall and blanket:

* A neutron multiplier, e.g., ^7\text{Li}, \ Pb, or \ Be, is needed to achieve tritium self-sufficiency.
Irradiation leads to an operating temperature window for material.

Additional considerations such as He embrittlement and chemical compatibility may impose further restrictions on operating window.
New structural material should be developed for fusion application

Candidate “low-activation” structural material:

- Fe-9Cr steels: builds upon 9Cr-1Mo industrial experience and materials database
  - 9-12 Cr ODS steel is a higher-temperature option.
- SiC/SiC: High risk, high performance option (early in its development path)
- W alloys: High performance option for PFCs (early in its development path)
Many Blanket Concepts have been considered

1) Ceramic Solid Breeder Concepts (using He coolant and ferritic steel structure)
   - Adopted from fission pebble-bed designs.
   - Complex internal design of coolant routing to keep solid breeder within its design window.
   - High structural content, low Li content, requires lots of Be multiplier.
   - Low outlet temperature and low efficiency
   - Large tritium inventory

2) Li (breeder and coolant) with vanadium structure
   - Needs insulating coating for MFE (MHD effects).
   - Special requirements to minimize threat of Li fires.
   - Large tritium inventory in Li which can be released during an accident.
3. Dual coolant with a self-cooled PbLi zone, He-cooled RAFS structure and SiC insert

- Steel First wall and partitioning walls are cooled with He.
- Most of fusion neutron energy is deposited in PbLi coolant/breeder.
- SiC insert separates PbLi from the walls: They reduce a) MHD effects and b) heating of the walls by LiPb
- Outlet coolant temperature of ~700°C (Max. steel temperature of ~550°C)
4. High-performance blanket with SiC Composite Structure and LiPb coolant

- 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 gross thermal efficiency of ~ 59% (52% net)
- Simple manufacturing technique.
- Very low afterheat.
- Class C waste by a wide margin.
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R&D Needs and Development Plan

No: Redesign

Yes: Balanced Assessment of Attractiveness & Feasibility

Scientific & Technical Achievements
Configuration & Maintenance
ARIES-AT (tokamak) Fusion Core

Cutaway of the ARIES-AT Fusion Power Core

Cross Section of ARIES-AT Power Core Configuration
The ARIES-AT utilizes an efficient superconducting magnet design

- On-axis toroidal field: 6 T
- Peak field at TF coil: 11.4 T
- TF Structure: Caps and straps support loads without inter-coil structure;

Superconducting Material

- Either LTC superconductor (Nb₃Sn and NbTi) or HTC
- Structural Plates with grooves for winding only the conductor.
Configuration & Maintenance are important aspects of the design

**vacuum vessel**

- Inner part: 4 pieces, welded during assembly
- Complete vessel, outer part is entirely made of maintenance ports

1. Install 4 TF coils at a time
2. Insert ¼ of inner VV and weld
3. Complete the torus
4. Insert maintenance ports and weld to inner part of VV and each other
5. Install outer walls and dome of the cryostat
Modular sector maintenance enables high availability

- Full sectors removed horizontally on rails
- Transport through maintenance corridors to hot cells
- Estimated maintenance time < 4 weeks
ARIES-AT Fusion core is segmented to minimize rad-waste and optimize functions.

Blanket-2 and shield are life-time components.
Safety, Licensing and Waste Disposal
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.

Level in Coal Ash
Safety analysis of off-normal events and accident scenarios indicate no evacuation plan is needed

- Detailed accident analysis (e.g., loss of coolant, loss of flow, double break in a major coolant line) are performed:
  - Limited temperature excursion due to the use of low-activation material.
  - No evacuation plan is needed. Most of the off-site dose after an accident is due to tritium release from fusion core. Fusion core tritium inventory is ~ 1kg.

- Components are designed to handle off-normal events:
  - Pressurization of blanket modules due internal break of He channels (Dual-cooled blanket)
  - Disruption forces and thermal loads
  - Quench of TF coils
Waste volume is modest (ARIES-AT)

- 1,270 m$^3$ of Waste is generated after 40 full-power year of operation.
  - Coolant is reused in other power plants
  - 29 m$^3$ every 4 years (component replacement), 993 m$^3$ at end of service
- Equivalent to ~ 30 m$^3$ of waste per full-power operation.
  - Effective annual waste can be reduced by increasing plant service life.

90% of waste qualifies for Class A disposal.
Costing is performed through a comprehensive cost break-down structure to component level.

Direct vendor quotes are used when available.

In the absence of vendor quotes, comparable technologies are used to cost a component.

Costing assumptions where calibrated against advanced fission and fossil plant economics.*

Magnetic Fusion Power Systems are projected to be cost-competitive.

- Total Capital Cost ranges from $4B to $8B.
- We are in the process of implementing Gen IV fission cost data base. This data base would lead:
  - Similar total Capital Cost
  - 30% lower COE because of a lower fixed-cost rate (5.8% for Gen-IV vs 9.65% for Delene).
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- Goals and Requirements
- Scientific & Technical Achievements

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  - Evaluation Based on Customer Attributes: Attractiveness
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Balanced Assessment of Attractiveness & Feasibility

If No: Redesign

Yes:
- R&D Needs and Development Plan
Technical Readiness Levels provides a basis for assessing the development strategy.

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<tr>
<th>Level</th>
<th>Generic Description</th>
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<tbody>
<tr>
<td>1</td>
<td>Basic principles observed and formulated.</td>
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<tr>
<td>2</td>
<td>Technology concepts and/or applications formulated.</td>
</tr>
<tr>
<td>3</td>
<td>Analytical and experimental demonstration of critical function and/or proof of concept.</td>
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<td>4</td>
<td>Component and/or bench-scale validation in a laboratory environment.</td>
</tr>
<tr>
<td>5</td>
<td>Component and/or breadboard validation in a relevant environment.</td>
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<td>6</td>
<td>System/subsystem model or prototype demonstration in relevant environment.</td>
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<tr>
<td>7</td>
<td>System prototype demonstration in an operational environment.</td>
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<tr>
<td>8</td>
<td>Actual system completed and qualified through test and demonstration.</td>
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<tr>
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<td>Actual system proven through successful mission operations.</td>
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See ARIES Web site: http://aries.ucsd.edu/aries/ (TRL Report) for detailed application of TRL to fusion systems.
Fusion Nuclear technologies are in an early development stage

- Fusion research has focused on developing a burning plasma.
  - Technology development has been based on the need of experiments as opposed to what is needed for a power plant.
- Plasma support technologies (e.g., superconducting magnets) are at a high-level of technology readiness level.
- Fusion Nuclear technologies, however, are at a low level of technology readiness level.
  - Material development has only focused on irradiation response of structural material due to the low level of funding.
  - A focused development program could raise the TRL levels of fusion nuclear technologies rapidly.
## Example: TRLs for Plasma Facing Components

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<tr>
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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>
<td>Design studies, basic research</td>
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<td>PFC concepts including armor and cooling configuration explored. Critical parameters characterized.</td>
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<td>Data from coupon-scale heat and particle flux experiments; modeling of governing heat and mass transfer processes as demonstration of function of PFC concept.</td>
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<td>Larger-scale facilities for submodule testing, High-temperature + all expected range of conditions</td>
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<td>Integrated large facility: Prototypical plasma particle flux+heat flux (e.g. an upgraded DIII-D/JET?)</td>
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<td>Integrated testing of the PFC concept subsystem in an environment simulating the integration of heat fluxes and particle fluxes at prototypical levels over long times.</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>Actual PFC system operation to end-of-life in fusion reactor with prototypical conditions and all interfacing subsystems.</td>
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Application of TRL to Power Plant Systems
Application to power plant systems highlights early stage of fusion nuclear technology development

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- Completed
- In Progress

Basic & Applied Science Phase

System demonstration and validation in operational environment (FNF)

For Details See ARIES Web site: http://aries.ucsd.edu/aries/ (TRL Report)
**ITER will provide substantial progress in some areas (e.g., plasma, safety)**

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System demonstration and validation in operational environment (FNF)

Absence of power-plant relevant fusion nuclear technologies severely limits ITER's contributions in many areas.
In summary:

- ITER will demonstrate “technical feasibility” of fusion power by generating copious amount of fusion power (500MW for 300s) with fusion power > 10 input power.
- Tremendous progress in understanding plasmas has helped optimize plasma performance considerably.
- Vision of attractive magnetic fusion power plants exists which satisfy customer requirements.
- Transformation of fusion into a power plant requires considerable R&D in material and fusion nuclear technologies (largely ignored or under-funded to date).
  - This step, however, can be done in parallel with ITER.
Thank You!