ARIES ACT1 Power Core Engineering

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and the ARIES Team

ANS 20th Topical Meeting on the Technology of Fusion Energy
30 August 2012
The ACT1 power core evolved from ARIES-AT (advanced physics and advanced technology)

Similarities

1. High performance plasma ($\beta_N=6\%$)
2. SiC composite breeding blanket with PbLi at $T_o\sim1000$ C
3. Brayton power cycle with $\eta\sim58\%$

Differences

1. Machine parameters, e.g. $R=6.25$ vs. $5.5$ m, smaller SOL
2. Power core design choices
   1. He-cooled W divertor
   2. Steel structural ring
   3. Separate vacuum vessel and LT shield
Plasma and material choices are aggressive, but the power density is modest (for a power plant)

<table>
<thead>
<tr>
<th></th>
<th>ACT1</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius</td>
<td>6.25</td>
<td>6.21</td>
</tr>
<tr>
<td>Aspect ratio</td>
<td>4</td>
<td>3.1</td>
</tr>
<tr>
<td>Toroidal field on axis</td>
<td>6</td>
<td>5.3</td>
</tr>
<tr>
<td>Normalized beta</td>
<td>5.75</td>
<td>1.8-2.8</td>
</tr>
<tr>
<td>Plasma current</td>
<td>10.9</td>
<td>15</td>
</tr>
<tr>
<td>Fusion power</td>
<td>1813</td>
<td>500</td>
</tr>
<tr>
<td>Thermal power</td>
<td>2016</td>
<td>651</td>
</tr>
<tr>
<td>Auxiliary power</td>
<td>154</td>
<td>110</td>
</tr>
<tr>
<td>Average n wall load</td>
<td>2.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Peak n wall load</td>
<td>3.6</td>
<td>0.7</td>
</tr>
<tr>
<td>Peak FW heat flux</td>
<td>0.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Peak divertor heat flux</td>
<td>10.6</td>
<td>10</td>
</tr>
<tr>
<td>Thermal conversion η</td>
<td>57.9</td>
<td>0</td>
</tr>
</tbody>
</table>
The power core replacement unit is self-supporting and maintained as a single unit

1. Internal parts are attached to a continuous steel ring.

2. All coolant access pipes are located at the bottom.

3. Sectors are moved on rails through large maintenance ports and transported in casks.

4. Immediate replacement with fresh sectors minimizes down time.

5. Main penalty is larger coils.
A He-cooled W-alloy divertor was chosen to allow high temperature and heat flux capability.

<table>
<thead>
<tr>
<th>Coolant</th>
<th>He</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant pressure</td>
<td>10 MPa</td>
</tr>
<tr>
<td>Surface power</td>
<td>277 MW</td>
</tr>
<tr>
<td>Volumetric power</td>
<td>26 MW</td>
</tr>
<tr>
<td>Peak surface heat flux</td>
<td>10-14 MW/m²</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>700 °C</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>800 °C</td>
</tr>
</tbody>
</table>

**Allowables:**

- W-alloy minimum: 800 °C
- W-alloy maximum: 1300 °C
- W armor maximum: 2190 °C
- Steel maximum: 700 °C

1. Jet cooling has been shown to accommodate up to 14 MW/m².
2. W-alloy development is needed.
The choice of divertor plate configuration is a tradeoff between performance and complexity.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Size</th>
<th>#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate</td>
<td>~1 m</td>
<td>$10^4$</td>
</tr>
<tr>
<td>T-tube</td>
<td>~10 cm</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Finger</td>
<td>~1.5 cm</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>

(results for 600/700°C He inlet/outlet temperature)
The plate divertor provides acceptable performance for peak heat flux \( \sim 10 \text{ MW/m}^2 \)

- Extensive jet flow modeling performed using both ANSYS and Fluent with various turbulence models
- Experimental verification performed at Georgia Tech (3 papers at this conference).
The breeding blanket uses annular pipes to maximize coolant outlet temperature

- Surface power: 128 MW
- Volumetric power: 1560 MW
- Peak surface heat flux: 0.3 MW/m²
- Peak wall load: 3.6 MW/m²
- Coolant: PbLi
- Inlet temperature: 740°C
- Outlet temperature: 1030°C
- SiC/SiC temp limit: 1000°C
- Peak pressure in blanket outer duct: 2.0 MPa
- Peak pressure across inner duct: 0.3 MPa
- SiC/SiC stress allowable: 190 MPa
3D MHD is a dominant force acting upon the coolant in insulated channel blankets.

\[
\begin{align*}
\text{inertia} & : \rho u^2 \\
\text{gravity} & : \rho g L \\
\text{wall shear} & : \sigma u B^2 L / H_a \\
\text{3D MHD} & : kN (\rho u^2)/2
\end{align*}
\]

<table>
<thead>
<tr>
<th></th>
<th>FW</th>
<th>core</th>
</tr>
</thead>
<tbody>
<tr>
<td>inertia</td>
<td>160,000</td>
<td>100</td>
</tr>
<tr>
<td>gravity</td>
<td>8x10^5</td>
<td>8x10^5</td>
</tr>
<tr>
<td>wall shear</td>
<td>190,000</td>
<td>475</td>
</tr>
<tr>
<td>3D MHD</td>
<td>3x10^6</td>
<td>7x10^5</td>
</tr>
</tbody>
</table>

**FW** core

<table>
<thead>
<tr>
<th></th>
<th>FW</th>
<th>core</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho)</td>
<td>10250</td>
<td>kg/m³</td>
</tr>
<tr>
<td>(\sigma)</td>
<td>7.6e5</td>
<td>Ω·m</td>
</tr>
<tr>
<td>(\mu)</td>
<td>6.5e-4</td>
<td>kg/(m·s)</td>
</tr>
<tr>
<td>(L)</td>
<td>8</td>
<td>m</td>
</tr>
<tr>
<td>(B)</td>
<td>8</td>
<td>T</td>
</tr>
<tr>
<td>(u)</td>
<td>4</td>
<td>0.1</td>
</tr>
<tr>
<td>(a)</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>(Ha)</td>
<td>8200</td>
<td>82,000</td>
</tr>
<tr>
<td>(Re_{</td>
<td></td>
<td>})</td>
</tr>
<tr>
<td>(N)</td>
<td>35</td>
<td>14,000</td>
</tr>
<tr>
<td>(k)</td>
<td>35</td>
<td>14,000</td>
</tr>
</tbody>
</table>

Return currents flowing outside field region.
Areas of concern for 3D effects

- 180° bends
- Varying field
- FW acceleration
- Manifolding and distribution

- Cryostat
- Vacuum pumping duct
- Vacuum vessel
- Saddle coil
- OB blanket
- TF coil
- Control coil
- Coolant ring headers
- He-cooled W divertor
- W vertical stabilizing shell
- W kink shell
- OB blanket-I
- OB blanket-II
- OB blanket of IB blanket
- LiPb manifold of IB blanket
- LiPb manifold of OB blanket-I
- LiPb manifold of OB blanket-II

Field entry/exit
Manifolding
Flow paths were designed to minimize 3D MHD effects by maintaining constant voltage

\[ V_{ab} = \int_{a}^{b} E \cdot dl = \int_{a}^{b} u \times B \cdot dl \]

\[ \Delta p_{3D} = kN\left(\frac{\rho u^2}{2}\right) \]

where \( k \) depends on wall conductance, pipe shape (e.g. circular or rectangular) and other details.

<table>
<thead>
<tr>
<th>Flow condition</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometrical change in a uniform magnetic field</td>
<td>0.25 - 2</td>
</tr>
<tr>
<td>Transverse field strength change (depending on abruptness)</td>
<td>0.1 – 0.2</td>
</tr>
<tr>
<td>Inlet or outlet manifold (Smolentsev et al)</td>
<td>1.5</td>
</tr>
</tbody>
</table>
3D MHD is difficult to avoid in the manifolds.

Outlet central ducts can be combined using relatively benign design elements.

Inlet to parallel FW channels is far more complex. Some form of orifice control is probably required.

e.g. MHD flow balancing:
Pressures and pressure drops for the ARIES-ACT1 IB blanket
(outboard $\Delta p_{mhd}$ will be lower)

- $4\text{ m} (0.4\text{ MPa})$
- $8\text{ m} (0.8\text{ MPa})$

- $\Delta p_{\text{bulk}} = 0$
- $\Delta p_{\text{FW}} = 0.2\text{ MPa}$
- $\Delta p_{\text{top}} = 0.1\text{ MPa}$
- $\Delta p_{\text{in}} = 0.45\text{ MPa}$
- $\Delta p_{\text{out}} = 0.2\text{ MPa}$

Heat exchanger
$\Delta p = 0.25\text{ MPa}$

1.2 MPa pump

$p > 0$
Computational approach for laminar heat transfer with variable flow

\[ u(x) \frac{\partial e(x,z)}{\partial z} = k \frac{\partial^2 T(x,z)}{\partial x^2} + Q(x) \]

\[ \frac{de}{dt} = k \frac{\partial^2 T}{\partial x^2} + Q - u \frac{\partial e}{\partial z} = 0 \]

FW and SW flows are mixed to create uniform central duct inlet temperature
Stagnation can occur in curved FW channels

- First order approximation to pressure gradient in an insulated duct.

\[ \nabla p = \frac{\sigma_f u B^2}{Ha} \quad \text{Ha} = aB\sqrt{\sigma/\mu} \]

- In a curved duct, Ha varies from front to back. So \( u \) also varies.

- The effect can be approximated by \( u \sim a \) (L. Buehler and L. Giancarli, “Magneto-hydrodynamic flow in the European SCLL blanket concept,” FZKA 6778, 2002).

- At a fixed volume flow rate, the pressure gradient increases by 50%.
Structures remain within their limits, with a modest variation from front to back.

- Outboard blanket-I
- 10 m length from bottom to top
- Radial and axial variations in volumetric heating
- Constant surface heat flux, constant properties
Primary stress analysis determines module dimensions and fabrication requirements.
Thermal stresses satisfy requirements

- Location is near the IB blanket bottom
- $3S_m$ rules for metal pressure vessels do not apply:
- We allocated 100 MPa for primary and 90 MPa thermal stress.
Power flows and bulk coolant temperatures in ARIES ACT1

η = 58%

- PbLi HX
- He HX
- FW blanket
- pump heat
- divertors
- primary side:
  - 303 MW
  - 10 MW
  - 1519 MW
- hot shields
- secondary side:
  - hot shields
  - recuperator
  - Heat sink
  - turbine
  - to He HX
  - from PbLi HX
  - 10 MW
  - 217 MW
  - 600 C
  - 650 C
  - 692 C
  - 700 C
  - 800 C
  - 733 C
  - 1000 C
  - 1030 C
Our Brayton cycle achieves ~58% efficiency

- Matching all of the coolant temperatures is needed.
- $\eta_{\text{recuperator}} = 96\%$, $\eta_{\text{turbine}} = 92\%$
- Result depends on inlet temperature as well as outlet; >57% could be achieved with 550°C inlet.
R&D Needs

• Characterization of steady and transient surface heat loads.

• MHD effects on flow and heat transfer, especially the inlet manifold.

• Fabrication, assembly and joining of complex structures made of SiC composites, tungsten alloys, and low activation ferritic steels.

• Mechanical behavior of steel, W and SiC structures, including fracture mechanics, creep/fatigue, and irradiation effects. Failure modes and rates.

• Determination of upper and lower temperature limits of W alloys and advanced ferritic steels.

• Fluence lifetime of components under anticipated loading conditions.

• Tritium containment and control.