Engineering Overview of ARIES ACT

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Topics

1. Power core materials and configuration.

2. Overall power balance and power conversion cycle.

3. Design strategies to minimize 3D MHD effects.

4. Cooling of curved first wall channels.
ARIES ACT power core and self-cooled PbLi (SCLL) SiC composite blanket
A He-cooled W-alloy divertor was adopted

1. PbLi cooling of the divertor limits the heat flux to ~5 MW/m² peak.
2. He-cooling can exceed 10 MW/m², and perhaps as high as 15 MW/m².
3. Our current reference concept is the combined plate/finger concept.

- Cartridges with both slots and fingers can be combined
- Limit fingers to zones with the highest heat flux (minimizes Δp)

$q<10 \text{ MW/m}^2$  $q>10 \text{ MW/m}^2$
He-cooled steel is used in the “Hot Shield”

- He-cooled steel offers a robust structural ring for sector integration.
- The divertor is already He-cooled, so He systems in place.
- Reduces MHD coolant routing problems significantly.
- Used for shielding.
- Operates at high temperature to contribute to power cycle.
- Inboard LM manifolding is embedded in the ring.
The Brayton cycle allows high efficiency with good safety features.

All of the PbLi and He power flows must be combined sensibly into an IHX.
Power flows and bulk coolant temperatures in ARIES ACT SCLL

(Preliminary values)

\[ \eta = 58\% \]

- FW blanket: 1565 MW
- He HX: 1000 C
- Hot shields: 228 MW
- Hot: 1030 C
- Cold: 740 C
- Divertors: 325 MW
- Hot: 800 C
- Cold: 700 C
- Pump heat: 6 MW
- Hot: 680 C
- Cold: 650 C
- Compressors: 17 MW
- Recuperator: to He HX, 600 C
- Heat sink: from PbLi HX, 1000 C
- Turbine:
Temperature restrictions on components reduces the power cycle performance.

Heat exchanger temperatures on the primary and secondary sides.

![Graph showing temperature restrictions on components]

- **Shield**
- **Divertor**
- **Blanket**

Temperature (C) vs. Power Transferred (0% to 100%).
Brayton cycle efficiency and power core inlet temperature

1000 C turbine inlet temperature

1050 C turbine inlet temperature

ARIES-AT operating point
3D MHD is the dominant force acting upon the coolant in insulated channel blankets

<table>
<thead>
<tr>
<th>Force</th>
<th>FW</th>
<th>blanket</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>inertia</td>
<td>$\rho u^2$</td>
<td>160,000</td>
<td>100</td>
</tr>
<tr>
<td>gravity</td>
<td>$\rho g L$</td>
<td>$8 \times 10^5$</td>
<td>$8 \times 10^5$</td>
</tr>
<tr>
<td>wall shear</td>
<td>$\sigma u B^2 L / H a$</td>
<td>190,000</td>
<td>475</td>
</tr>
<tr>
<td>3D MHD</td>
<td>$k N (\rho u^2) / 2$</td>
<td>$3 \times 10^6$</td>
<td>$7 \times 10^5$</td>
</tr>
</tbody>
</table>

FW core

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>$\rho$</td>
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<tr>
<td>$\sigma$</td>
<td>7.6e5</td>
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<tr>
<td>$\mu$</td>
<td>6.5e-4</td>
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<tr>
<td>$B$</td>
<td>8</td>
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<tr>
<td>$u$</td>
<td>4</td>
</tr>
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<td>$a$</td>
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<tr>
<td>$H a$</td>
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<tr>
<td>$R e_{</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>35</td>
</tr>
<tr>
<td>$k$</td>
<td>1</td>
</tr>
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</table>
Semi-empirical formulation of 3D MHD effects

\[ \Delta p_{3d} = k \, N \left( \rho \nu^2/2 \right) \]

where \( N = H \alpha^2 / Re \), and \( k \) is a semi-empirical constant

- For flows with geometrical changes in a uniform magnetic field \( 0.25 < k < 2 \).
- For a change in transverse field strength \( k \approx 0.1-0.2 \) (depending on the abruptness of the change in \( B \)).
- For an inlet or outlet manifold, Smolentsev et al used \( k=1.5 \).
- Depends on wall conductance, pipe shape (e.g. circular or rectangular) and other details.


To keep 3d effects low, maintain constant voltage

\[ \int u \times B \cdot dl \]
Areas of concern for 3D effects

Field entry/exit

Manifolding

Expansion

Manifolding and distribution

180° bends
Design Strategies

- 180° bends are acceptable, if they are perpendicular to B
- Use expansions and contractions to reduce velocity in manifolds
- Channel size reduction for field entry/exit
- Careful design of the manifolds (see next slides).
Inboard manifolding is embedded in the high temperature shield (i.e., the structural ring)
Manifolds consist of successive splits and toroidal movements with poloidal component

- Coaxial pipes everywhere
- Gradual toroidal motions
- Some complex flows will require further analysis:
  - FW manifolds
  - channel splits
Stagnation can occur in curved FW channels

- First order approximation to pressure gradient in an insulated duct.
  \[ \nabla p = \frac{\sigma_f u B^2}{Ha} \quad Ha = aB \sqrt{\frac{\sigma}{\mu}} \]

- 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).

- For constant volume flow rate, the pressure gradient increases by 50%.

- The full conduction/convection heat transfer equation with transverse varying velocity was solved by finite difference to determine the magnitude of this effect on heat transfer.
Convective heat transfer with laminar slug flow

Energy balance equation (internal energy $e=\rho C_p T$):

$$\rho u \frac{\partial e}{\partial z} = k \frac{\partial^2 T}{\partial x^2}$$

Exact solution for constant velocity on a semi-infinite plane is equivalent to transient 1D conduction:

$$T(x,t) - T_i = \frac{2q^* (\alpha t / \pi)^{1/2}}{k} \exp\left(-\frac{x^2}{4 \alpha t}\right) - \frac{q^* x}{k} \text{erfc}\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

Example slug result:

$T$ vs. $z/v$ for several $x,$ $q^*=0.2$ MW/m$^2,$ $u=4.2$ m/s, $L=8.3$ m
Computational approach for 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
Effect of stagnation on wall temperatures

Exit temperature vs. depth

Surface temperature vs. length

- Peak velocity is 6.3 m/s for a 4.2 m/s average, $q''=0.2$ MW/m²
- $\Delta p$ is 50% higher than slug flow case.
- Peak surface temperature increases by only about 20°C.
1-dimensionalized FW velocity profile

\( \langle v \rangle = 2.66 \text{ m/s in FW channel} \)

Worst case profile that conserves \( \langle v \rangle \)

All other channels have constant velocity (0.094 m/s center, 0.266 m/s SW)
Results (radial profiles)
Results (axial profiles)
Pressures and pressure drops for the ARIES SCLL IB blanket

(outboard $\Delta p_{mhd}$ will be lower)

4 m (0.4 MPa)

$\Delta p_{out} = 0.2$ MPa

$\Delta p_{bulk} = 0$

8 m (0.8 MPa)

$\Delta p_{FW} = 0.2$ MPa

$\Delta p_{top} = 0.1$ MPa

1.2 MPa pump

$\Delta p_{in} = 0.45$ MPa

$p > 0$

$\Delta p = 0.25$ MPa
Summary of SCLL power core findings

- An advanced SiC/SiC\textsubscript{f} blanket design with He-cooled W-alloy divertor and steel structural shield was selected for ARIES ACT (SCLL).

- Detailed analysis of various MHD flow concerns has been performed:
  - MHD pressure drop can be low (<1 MPa), only if 3D effects are avoided.
  - Designs are possible with only one source of 3D effects: the manifolds.
  - The pressure drop and flow distribution caused by this 3D source are uncertain, requiring further R&D (and a fully-detailed design).
  - Stagnated flow in curved ducts was shown to be acceptable.

- 58% thermal conversion efficiency is achievable with this design.
Extras
Strong poloidal magnetic fields exist both inside and outside the TF coils.

The plasma is modeled as a discrete ring.

(PF coil currents from ARIES-AT)
Poloidal fields as high as 4 T exist along the liquid metal flow.

Not only are there large poloidal fields, but also significant gradients along and within the pipes.