SPIRAL BLANKET

A Novel Idea with Potential for High Neutron Wall Loading in a Dry Wall Blanket Design

APEX Task IV

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Scope of Study

• The spiral blanket is proposed as one possible option for consideration for a dry wall blanket design by group IV of the APEX study.

• This is a scoping exercise to determine the limits of neutron wall loading potential in a dry wall configuration.

• The study direction is to use nano-composite ferritic steel as the structural material and the low viscosity FLIBE as a coolant.

• Maximum steel/FLIBE interface temperature $\leq 700^\circ$C and maximum steel temperature $\leq 800^\circ$C.
General Description

• The ARIES-AT reactor dimensions have been used. The blanket consists of modules extending poloidally from the bottom to the top of the chamber.
  - Total module height along the curvature is 6.7 m
  - Module cross section at midplane is 0.3 m x 0.3 m
  - Module cross section at extremities is 0.3 m radially x 0.22 m toroidally

• The blanket module is equipped with spiral discs ramping up from the bottom to the top. The FLIBE coolant enters on the bottom then travels on the spiral and is rotated from the rear of the module to the front, then back to the rear all the way to the top, where it finally exits the module. The coolant then travels back down through a second module located behind the first module.

• The 3 mm thick first wall is scalloped with semi-cylindrical projections inclined in the direction of coolant flow. The scallops start in the middle of the side wall and continue around the FW to the middle of the opposite side wall. At the FW the geometry resembles a smooth round tube providing an unimpeded path for the coolant.
Spiral Blanket for ARIES AT Reactor Dimensions

- Overall vertical height (following curvature) 6.7 m
- Spiral screw is made of Be, vol. fraction 20%.
- Module toroidal width at mid-plane = 0.3 m and at extremities = 0.22 m.
- Coolant average velocity at mid-plane = 4 m/s
Expanded Views of Spiral Blanket

Front view from the plasma side

Side view with exposed internal spiral discs
Description (contd.)

• The discs are composed of two formed steel sheets enclosing a Be pebble bed. The sheets are formed as an upper and a lower cladding which when sandwiched together provide the space for the Be pebbles. The discs are fabricated individually and mounted on the shaft separately with the interface between adjacent discs located in the back of the module. When assembled together, the discs form a helical spiral.

• The disc’s shape ranges from near square at the midplane to near rectangular at the extremities. In cross section the discs are tapered with a large dimension near the shaft, tapering to a small dimension at the FW. The discs come close to the inner ridges of the FW but do not make contact.

• Finally the disc’s cladding is perforated with slits in the direction of coolant flow. This allows free coolant access to the Be pebble bed for cooling and for reducing the $T_2$ partial pressure in the vicinity of the Be pebbles.
Mid-Plane Near Square Disc for Spiral Blanket

At mid-plane the discs are near square with a rounded side facing the first wall. Towards the extremities, the discs have the same radial depth but are narrower in the toroidal direction. Perforations in both upper and lower cladding run in the direction of flow and allow coolant to circulate through the Be pebble bed for cooling and for reducing the T2 partial pressure in the vicinity of the Be pebbles.
Cross-section of Disc Shows the Encapsulated Be Pebble Bed

Disc cross-section shows the Be pebble Bed occupying a volume fraction of 65%. The figure shows the cladding as made of two halves which are sandwiched together to provide the space for the Be pebble bed. Each disc is fabricated separately and then mounted and fixed to the shaft. The disc is tapered with the thickest section at the shaft, tapering down toward the FW.

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Evolution of the Design

● Why A Scalloped Wall?

There are two good reasons:

1) By scalloping, the FW is reinforced, as in the case of corrugated sheeting. This makes it possible to have a free-standing FW with no need for reinforcement across the 30 cm span and no need for welds facing the plasma which will compromise the structural integrity of the FW.

2) The semi-cylindrical shapes of the scallops provide a smooth turning geometry for the coolant at the FW where the velocity is high resulting, in good heat transfer and a lower pressure drop.

● Why a Be Pebble Bed?

– The original design called for Be or Be-alloy discs. However, because of swelling and embrittlement concerns, the idea was abandoned.

– A Be pebble bed enclosed in steel cladding provides a uniform distribution of Be in the module and avoids the issues of swelling and embrittlement.
Dynamic Viscosity of Flibe (LiF)n.(BeF2) as a Function of Temperature

Viscosity of Flibe taken from Summary of Physical Properties for Lithium, Pb-17Li, and (LiF)n.BeF2 Coolants
S. J. Zinkle

Dynamic Viscosity of Flibe
= 5.94 x 10e-4 exp(4605/T) g/cm.s for N=2 and T= 740-860 K
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Poloidal height along module (m)</td>
<td>6.7</td>
</tr>
<tr>
<td>Midplane cross section of module (cm x cm)</td>
<td>30 x 30</td>
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<tr>
<td>Extremities cross section of module (cm x cm)</td>
<td>30 x 23</td>
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<tr>
<td>First wall thickness (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Dimension of scallop (cm)</td>
<td>6.7</td>
</tr>
<tr>
<td>Avg. thickness of disc (cm)</td>
<td>3.0</td>
</tr>
<tr>
<td>Disc thickness at FW (cm)</td>
<td>1.0</td>
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<tr>
<td>Disc thickness at shaft (cm)</td>
<td>5.0</td>
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### Spiral Blanket Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Channel height at FW (cm)</td>
<td>6.72</td>
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<td>Channel height at shaft (cm)</td>
<td>4.22</td>
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<td>Number of discs</td>
<td>70</td>
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<td>Avg. fluid path length (m)</td>
<td>32.9</td>
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<tr>
<td>Hydraulic diameter of channel (cm)</td>
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<tr>
<td>Disc cladding thickness (mm)</td>
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<tr>
<td>Steel shaft diameter (cm)</td>
<td>3.0</td>
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<td>Be pebble bed packing fraction</td>
<td>0.65</td>
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Three Cases Have Been Analyzed

<table>
<thead>
<tr>
<th></th>
<th>5 MW/m² Nominal Peak</th>
<th>10 MW/m² Nominal Peak</th>
<th>5 MW/m² Average</th>
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<tr>
<td>Max. NWL (MW/m²)</td>
<td>4.77</td>
<td>9.54</td>
<td>7.45</td>
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<tr>
<td>Avg. NWL (MW/m²)</td>
<td>3.19</td>
<td>6.38</td>
<td>5.0</td>
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<td>Max. surface heat. (MW/m²)</td>
<td>0.622</td>
<td>1.24</td>
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<tr>
<td>Midplane mid-channel velocity (m/s)</td>
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<td>3.3</td>
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<tr>
<td>Velocity at FW (m/s)</td>
<td>5.0–5.75</td>
<td>5.5–6.3</td>
<td>5.5–6.3</td>
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<td>Coolant inlet temp. (°C)</td>
<td>610</td>
<td>500</td>
<td>542</td>
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<tr>
<td>Coolant exit temp. (°C)</td>
<td>660</td>
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<td>613</td>
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<td>Coolant temp. to HE (°C)</td>
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<td>600</td>
<td>620</td>
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<td>Max. steel temp. (°C)</td>
<td>754</td>
<td>800</td>
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<td>Max. interface/FLIBE temp. (°C)</td>
<td>700</td>
<td>694</td>
<td>682</td>
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<td>Pressure drop (MPa)</td>
<td>0.47</td>
<td>0.56</td>
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</table>
Operating Temperature of Spiral Blanket at 5 MW/m² Nominal Peak NWL

Poloidal Distance (m)

Temperature (°C)

Outer Surface
5 MW/m² N.Load

Avg. Neutron Wall Loading is 3.19 MW/m²
Peak Neutron Wall loading is 4.8 MW/m²
Surface Heating 15% of Avg. NWL with a peaking factor of 1.3

Inner Surface
5MW/m² N.Load

Flibe Temp.
Operating Temperature of Spiral Blanket at 10 MW/m² NWL

Poloidal Distance (m)

Temperature (°C)

Outer Surface 10MW/m² NWL

Inner Surface 10MW/m² NWL

Flibe Temp.

Avg. NWL 6.38MW/m²
Peak NWL 9.6MW/m²
Surf. Heat 15% of Avg. NWL with peak factor of 1.3

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Operating Temperature of Spiral Blanket at 5.0 MW/m² Average Neutron Wall Loading and 1.0 MW/m² Peak Surface Heating

Poloidal NWL distribution and Surface heating as in ARIES-AT
Mid-plane mid-channel velocity 3.3 m/s
Neutron Wall Loading and Surface Heating Distribution in the Poloidal Direction for 5.0 MW/m² Avg. NWL and 1.0 MW/m² Surf. Heat

Wall Loading (MW/m²) vs. Poloidal Distance Along Blanket (m)

NWL and Surface Heat Distribution as in ARIES-AT Reactor Design

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Coolant Velocity at First Wall as a Function of Poloidal Distance Along the Blanket for 5 MW/m² Average NWL

<table>
<thead>
<tr>
<th>Poloidal Distance Along Blanket (m)</th>
<th>Velocity (m/s)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>1</td>
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<tr>
<td>7</td>
<td></td>
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<tr>
<td>8</td>
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</table>

velocity at FW

Velocity at FW

Mid-Plane Mid-channel
Velocity 3.3 m/s
Avg.NWL 5.0 MW/m²
Peak Surface
Heat Flux 1 MW/m²
Reynolds Numbers and Heat Transfer Coefficients as a Function of Poloidal Distance Along Blanket

Avg.NWL 5.0 MW/m²
Peak Surf.Heat 1.0MW/m²
Mid-Plane Mid-Channel
Velocity 3.3 m/s
Preliminary Neutronics Analysis for the Spiral Blanket

- 5 mm FS FW
- 30 cm thick Spiral Blanket:
  - 75% Flibe
  - 20% Be
  - 5% FS
- 45 cm thick Secondary Blanket:
  - 95% Flibe
  - 5% FS

- Local OB TBR = 1.36 with natural Li in the Flibe
- Local IB TBR = 1.16 with natural Li in the Flibe
- Energy Multiplication M = 1.18 in spiral blanket
- Energy Multiplication M = 1.32 in spiral and secondary blankets

For 5 MW/m² peak neutron wall loading:
- Peak nuclear heating in FS FW 43 W/cm³
- Peak nuclear heating in spiral blanket 39 W/cm³
- Average nuclear heating in spiral blanket 17 W/cm³
- Peak FW dpa rate 58 dpa/FPY
- Peak dpa rate in secondary blanket 3.2 dpa/FPY (96 dpa at end-of-life)
- Peak He production in Be spiral 18,400 appm/FPY
- Peak T production in Be spiral 200 appm/FPY

Doubling neutron wall loading to 10 MW/m² results in:
- Doubling nuclear heating and damage rates
- Doubling replacement frequency of spiral blanket
- For 200 dpa limit secondary blanket remains lifetime component and spiral blanket thickness does not need to be increased
Reducing Be content to 15% results in:
- Reducing local OB TBR to 1.31
- Some of TBR reduction can be recovered by enriching Li
- Enriching to 30% $^6\text{Li}$ yields local OB TBR of 1.34

Using Flinabe instead of Flibe results in:
- ~15% reduction in TBR
- Local OB TBR with Flinabe (nat. Li) and 20% Be in spiral blanket is 1.17
- Flinabe is less effective in shielding than Flibe
- End-of-life peak dpa in secondary blanket is 112 dpa for 5 MW/m$^2$
- Enriching Li in the Flinabe enhances TBR
- Enriching to 50% $^6\text{Li}$ yields TBR of 1.29 with 20% Be in spiral blanket

Conclusions:

⇒ With 20% Be in 30 cm thick Flibe spiral blanket
   TBR is adequate and secondary blanket is lifetime component even with 10MW/m$^2$ wall loading

⇒ Reducing Be content should be accompanied by enriching Li (Trade-off!!)

⇒ Using Flinabe requires significant enrichment with at least 20% Be in addition to added safety concerns from Na activation

M. Sawan
3/27/02
1) **Spiral blanket (Igor's design)**

I have used a corrugated section (Fig. 1) for calculations using a beam theory with a toroidal span of 30 cm. The bending shape factor $K$ for the section shown in Fig. 1 is 1.47. Fig. 2a-b show the variation of $P_b/K$ and $P_b/K_{eff}$ with first wall thickness for a coolant pressure of 0.56 MPa. It is evident that a 3 mm thick first wall is acceptable for 12YWT but not for MA957.

![Diagram of corrugated spiral blanket first wall](image)

*Figure 1. Corrugated spiral blanket first wall (Igor's design).*

![Graphs of stress variations](image)

*Figure 2. Variation of (a) modified primary bending ($P_b/K$) stresses and (b) modified primary bending stresses ($P_b/K_{eff}$) with first wall thickness for Igor's spiral blanket design.*
Ranges for Calculating Coefficients of Resistance in Curved Flow Geometries

(Handbook of Hydraulic Resistance, I. E. Idelchik)

1) \(50 < \text{Re}^{0.5} (D_h/2R_o) < 600\)

\[f = \frac{20}{\text{Re}^{0.65}} (D_h/2R_o)^{0.175}\]

2) \(600 < \text{Re}^{0.5} (D_h/2R_o) < 1400\)

\[f = \frac{10.4}{\text{Re}^{0.55}} (D_h/2R_o)^{0.225}\]

3) \(1400 < \text{Re}^{0.5} (D_h/2R_o) < 5000\)

\[f = \frac{5}{\text{Re}^{0.45}} (D_h/2R_o)^{0.275}\]

4) \(5000 < \text{Re}^{0.5} (D_h/2R_o) < 14000\)

\[f = \frac{2}{\text{Re}^{0.35}} (D_h/2R_o)^{0.32}\]
Coefficients of Friction for Spiral Blanket as a Function of Reynold's Number for a Hydr.Diam. Dh=8.57 cm and Radius of Curvature Ro=17 cm

Taken from Handbook of Hydraulic Resistance
I.E.Idel'chik
Pressure Drop in spiral blanket

For the range $5000 < \text{Re} \sqrt{\frac{D_h}{2R_0}} < 14000$, the friction coefficient is

$$f = \frac{2}{\text{Re}^{0.35}} \left(\frac{D_h}{2R_0}\right)^{0.32}$$

Where $D_h$ is the hydraulic diameter of the channel = 8.6 cm and $R_0$ is the radius of curvature = 17 cm.

$$\text{Re} = 28280$$

$$f = (0.055)(0.64) = 0.035$$

for $v = 3.0 \text{ m/s}$ \hspace{1cm} $\Delta P = 0.496 \text{ MPa}$.

for $v = 3.3 \text{ m/s}$ \hspace{1cm} $\Delta P = 0.600 \text{ MPa}$
Conclusions

• The spiral blanket is a novel idea for a fusion reactor suitable for non-electrically conducting coolants such as FLIBE.
• It has the promise of achieving high neutron wall loading up to a nominal peak of 10 MW/m².
• Coolant outlet temperature ranges from 600°C at 10 MW/m² nominal peak to 665°C at 5 MW/m² nominal peak and is suitable for a supercritical steam power cycle with an efficiency of 47-50%.
• Be pebble beds are being investigated in the Jupiter program.

Possible issue

Designing the Be pebble bed to operate in a temperature and $T_2$ partial pressure mode such that it does not accumulate $T_2$.