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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APEX Quarterly Meeting
April 17–19, 2002
San Diego CA

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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 ≤ 700ºC and maximum steel temperature ≤800°C.

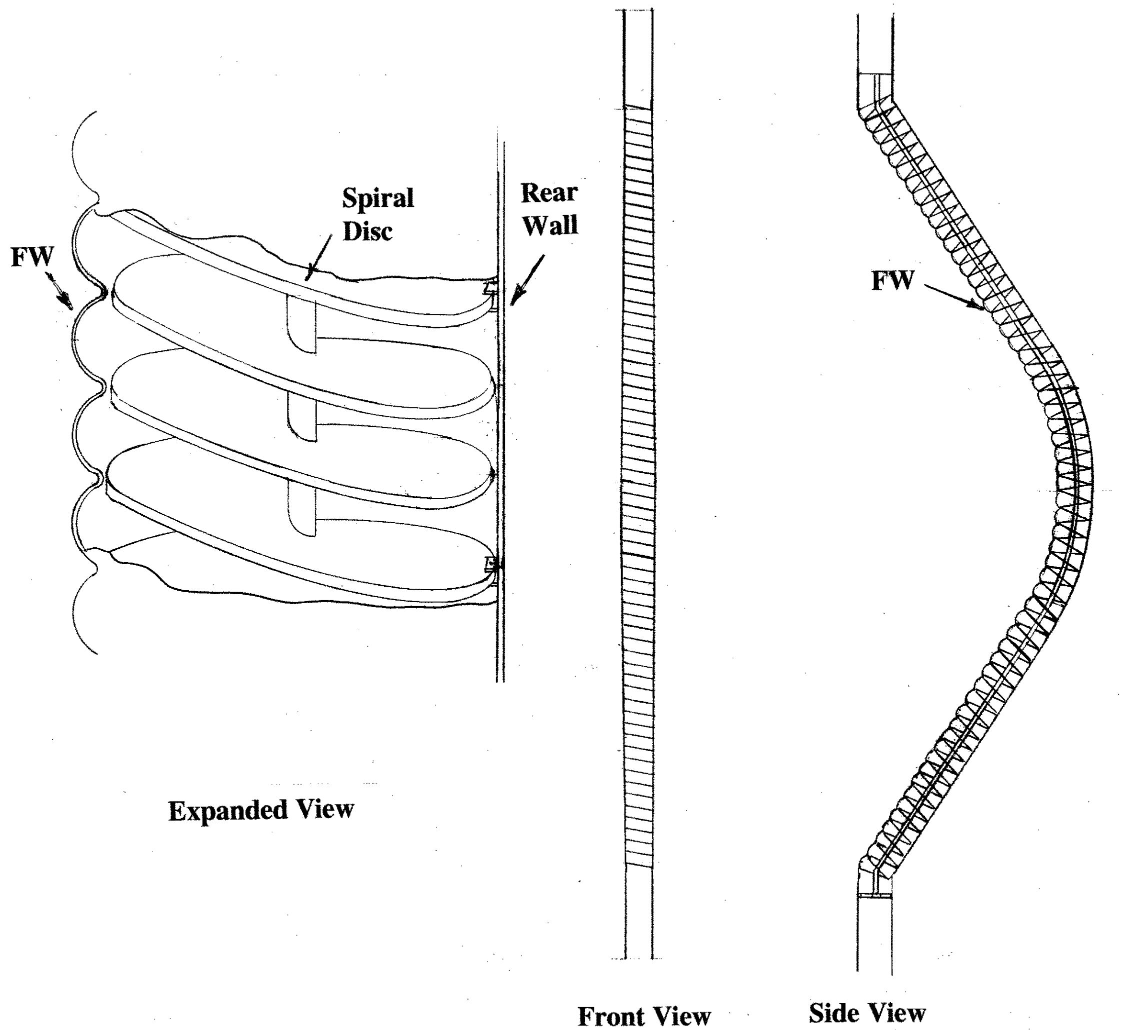
General Description

- 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.

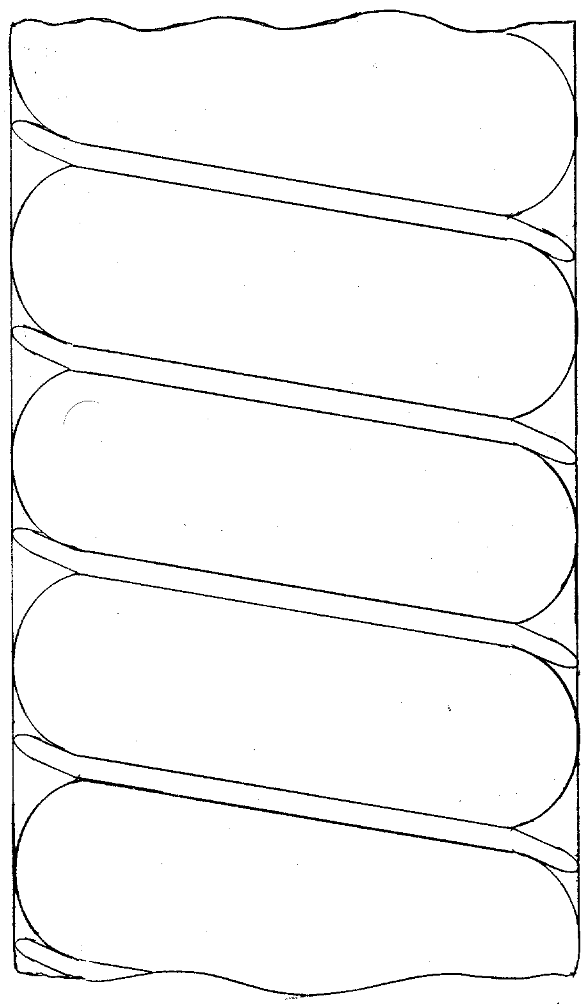
- The 3 mm thick first wall is scalloped with semi-cylindrical projections inclined in the direction of coolant flow. The scallops start in the middle of the side wall and continue around the FW to the middle of the opposite side wall. At the FW the geometry resembles a smooth round tube providing an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

Spiral Blanket for ARIES AT Reactor Dimensions

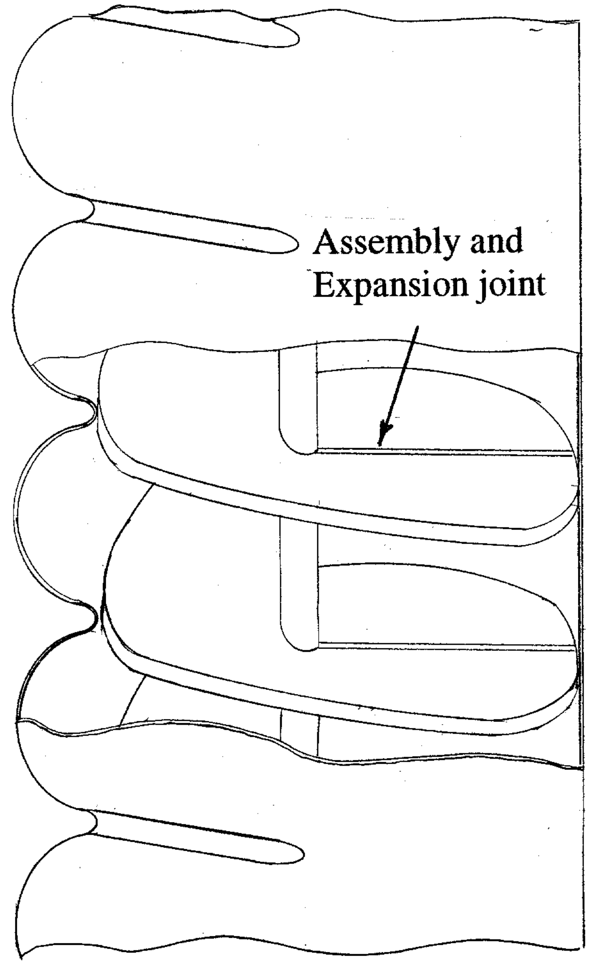


Overall vertical height (following curvature) 6.7 m
Spiral screw is made of Be, vol. fraction 20 %.
Module toroidal width at mid-plane = 0.3 m and
at extremities = 0.22 m.
Coolant average velocity at mid-plane = 4 m/s

Expanded Views of Spiral Blanket



Front view from the plasma side



Side view with exposed internal spiral discs

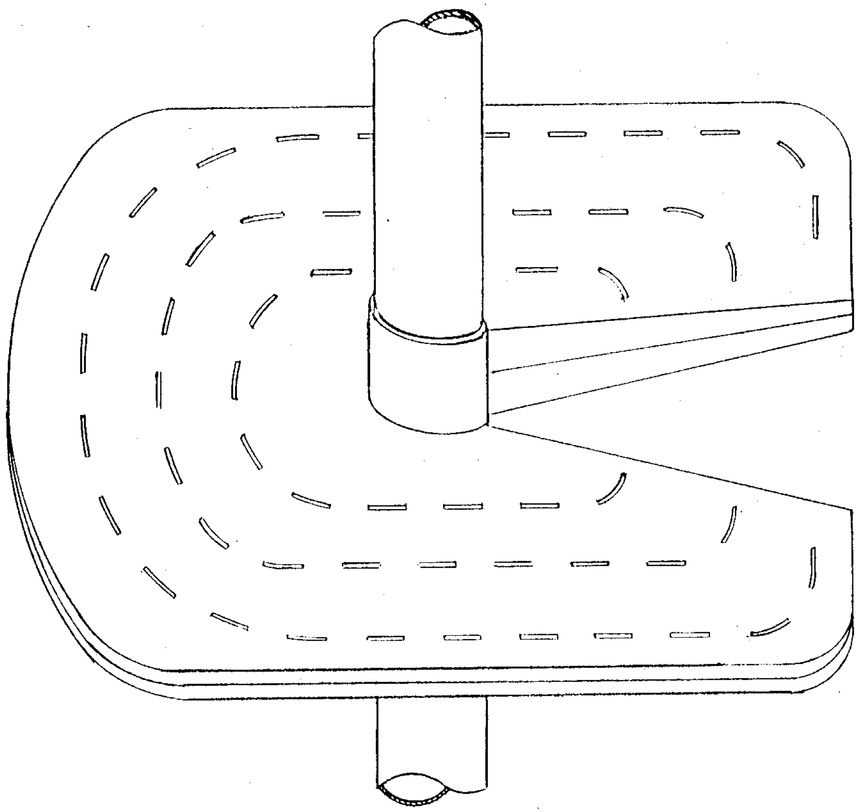
Description (contd.)

- **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.**

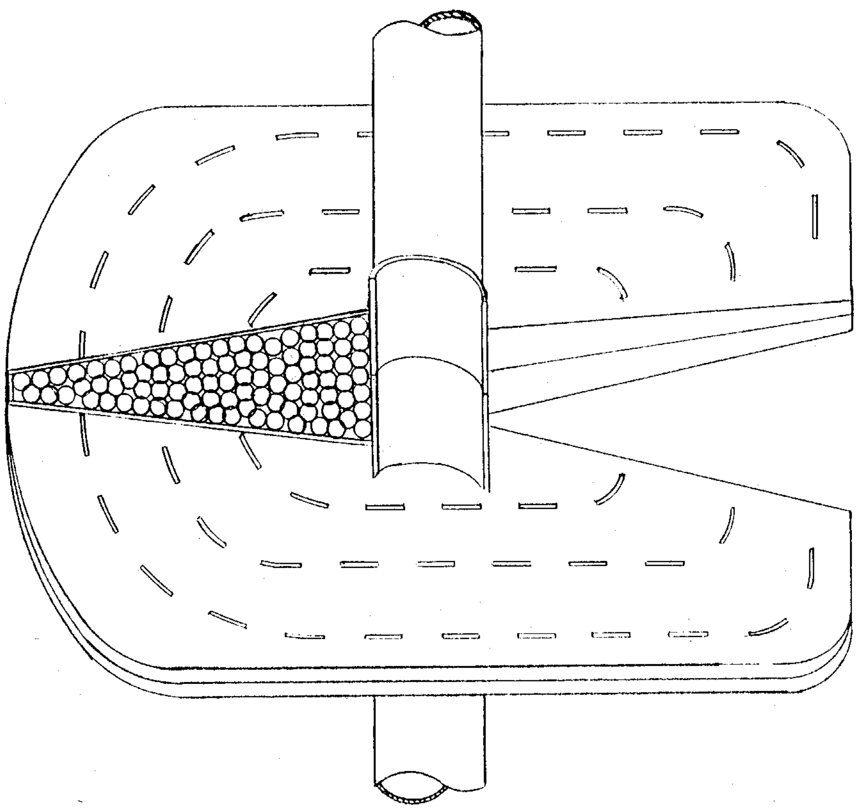
- **Finally the disc's cladding is perforated with slits in the direction of coolant flow. This allows free coolant access to the Be pebble bed for cooling and for reducing the T_2 partial pressure in the vicinity of the Be pebbles.**

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 narower 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.

Evolution of the Design

- **<u>Why A Scalloped Wall?</u>**

  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.**

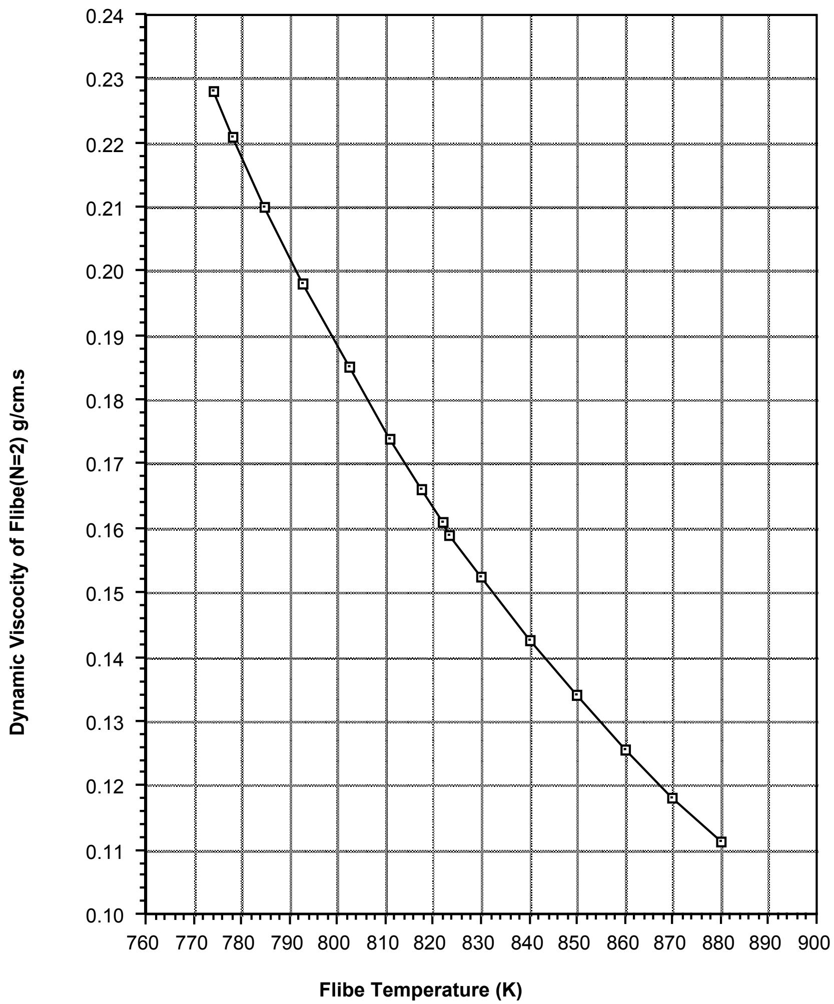
  2) **The semi-cylindrical shapes of the scallops provide a smooth turning geometry for the coolant at the FW where the velocity is high resulting, in good heat transfer and a lower pressure drop.**

- **<u>Why a Be Pebble Bed?</u>**

  – **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



Dynamic Viscosity of Flibe
= 5.94 X 10e-4 exp(4605/T) g/cm.s for N=2 and
T= 740-860 K

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

Spiral Blanket Parameters

Poloidal height along module (m)	6.7
Midplane cross section of module (cm x cm)	30 x 30
Extremities cross section of module (cm x cm)	30 x 23
First wall thickness (mm)	3
Dimension of scallop (cm)	6.7
Avg. thickness of disc (cm)	3.0
Disc thickness at FW (cm)	1.0
Disc thickness at shaft (cm)	5.0

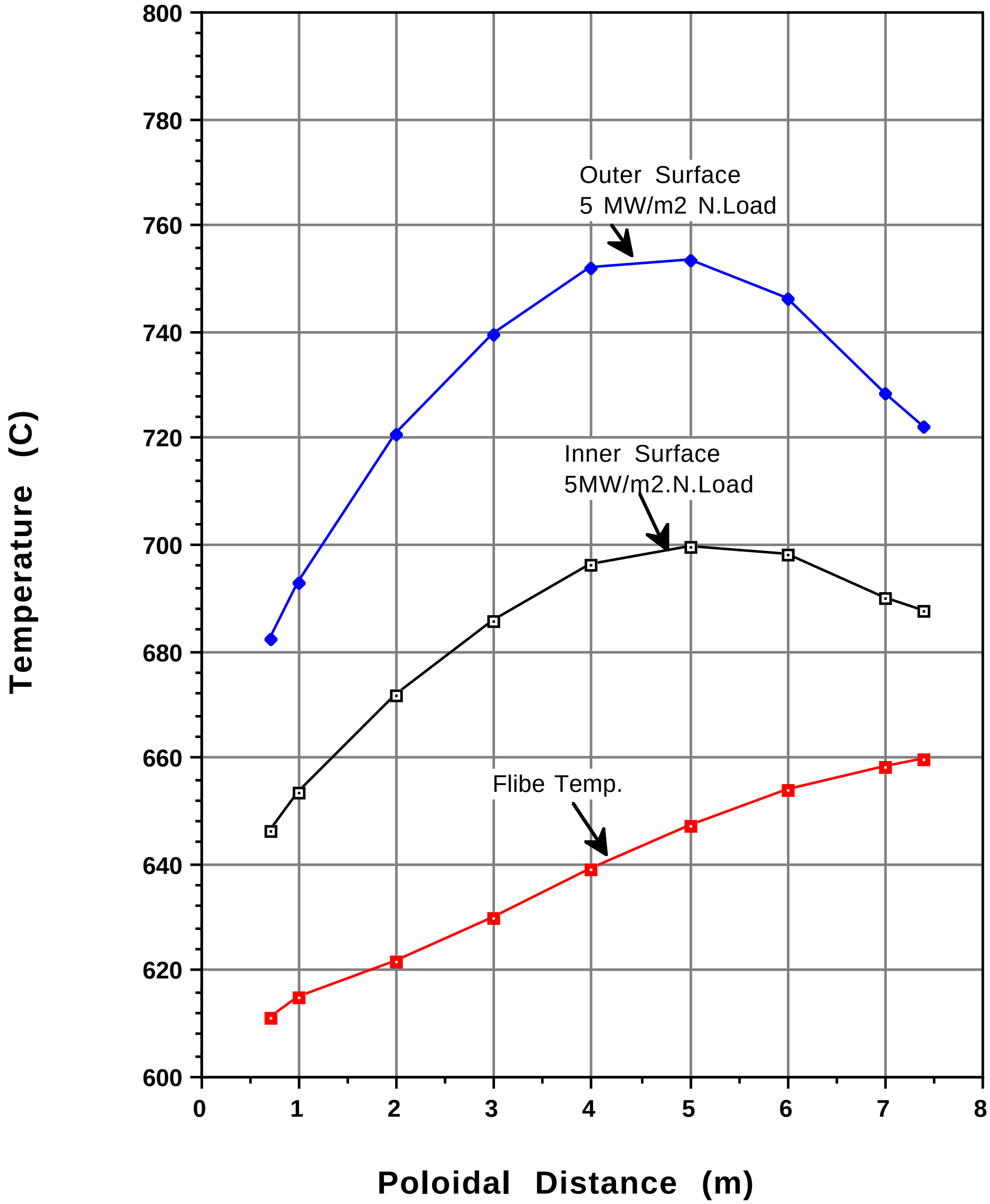
Spiral Blanket Parameters

Channel height at FW (cm)	**6.72**
Channel height at shaft (cm)	**4.22**
Number of discs	**70**
Avg. fluid path length (m)	**32.9**
Hydraulic diameter of channel (cm)	**8.6**
Disc cladding thickness (mm)	**1.0**
Steel shaft diameter (cm)	**3.0**
Be pebble bed packing fraction	**0.65**

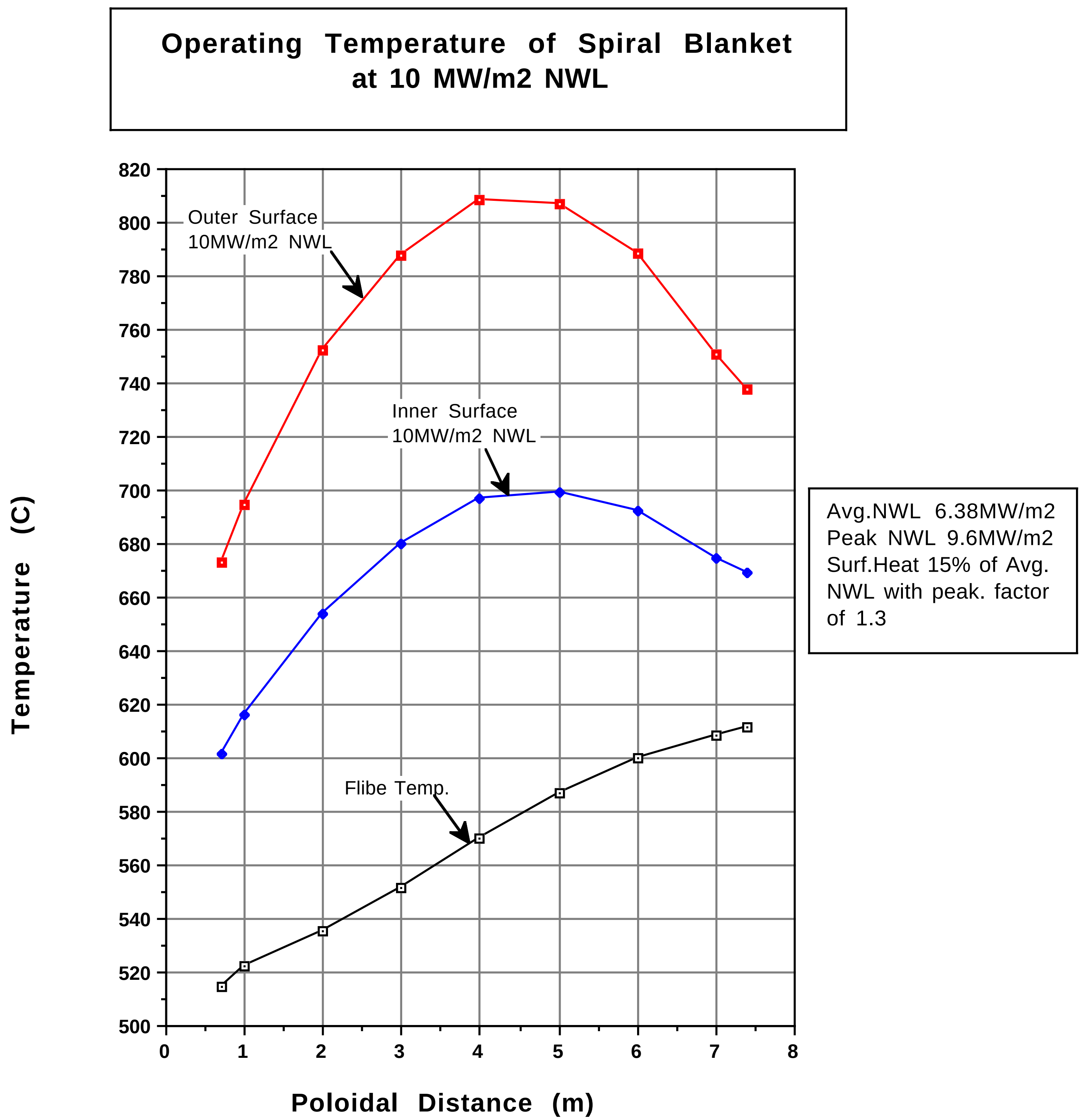
Three Cases Have Been Analyzed

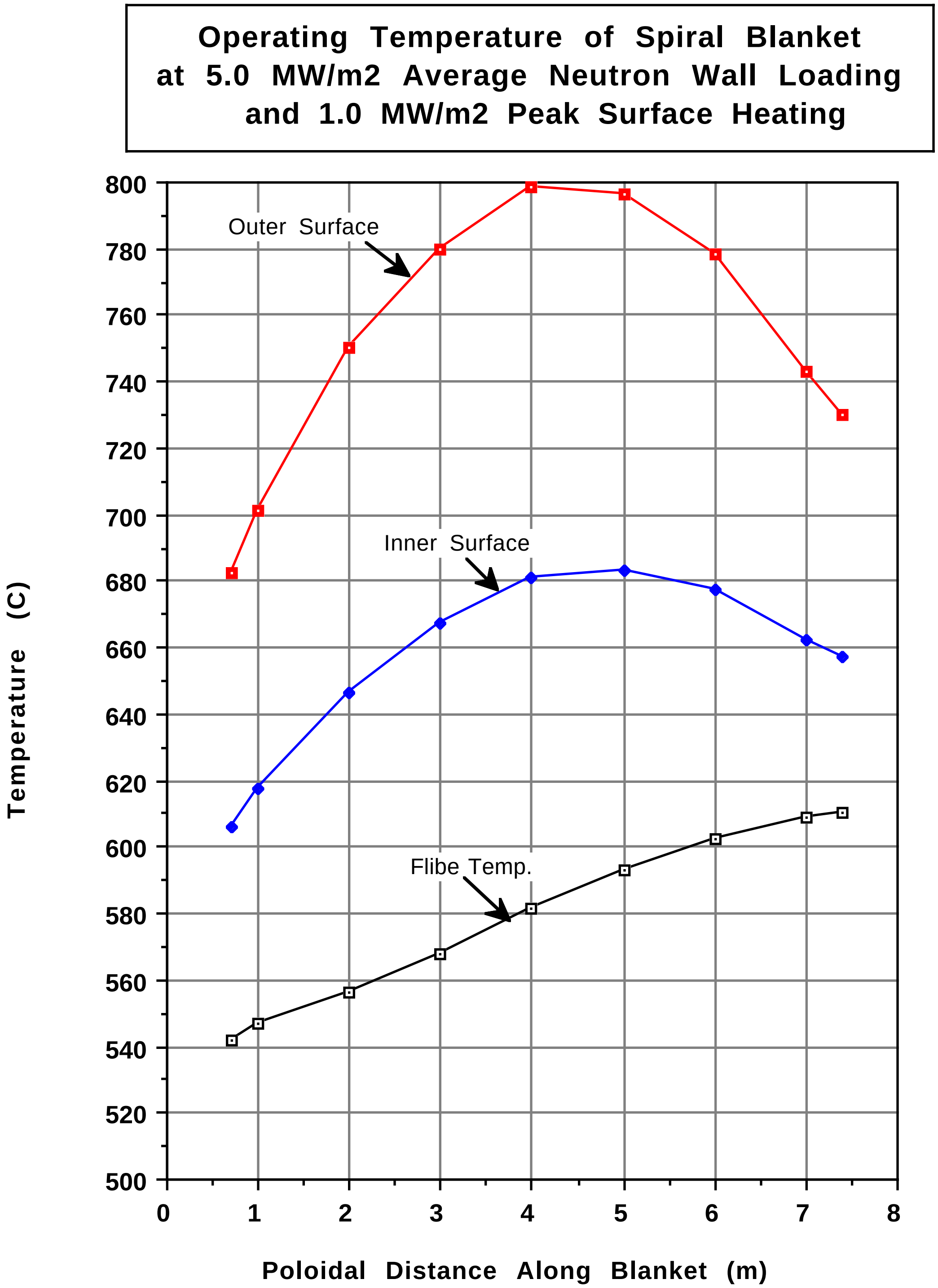
	5 MW/m^2 Nominal Peak	10 MW/m^2 Nominal Peak	5 MW/m^2 Average
Max. NWL (MW/m^2)	4.77	9.54	7.45
Avg. NWL (MW/m^2)	3.19	6.38	5.0
Max. surface heat. (MW/m^2)	0.622	1.24	1.0
Midplane mid-channel velocity (m/s)	3.0	3.3	3.3
Velocity at FW (m/s)	5.0–5.75	5.5–6.3	5.5–6.3
Coolant inlet temp. (^oC)	610	500	542
Coolant exit temp. (^oC)	660	590	613
Coolant temp. to HE (^oC)	665	600	620
Max. steel temp. (^oC)	754	800	800
Max. interface/FLIBE temp. (^oC)	700	694	682
Pressure drop (MPa)	0.47	0.56	0.56

Operating Temperature of Spiral Blanket at 5 MW/m2 Nominal Peak NWL



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

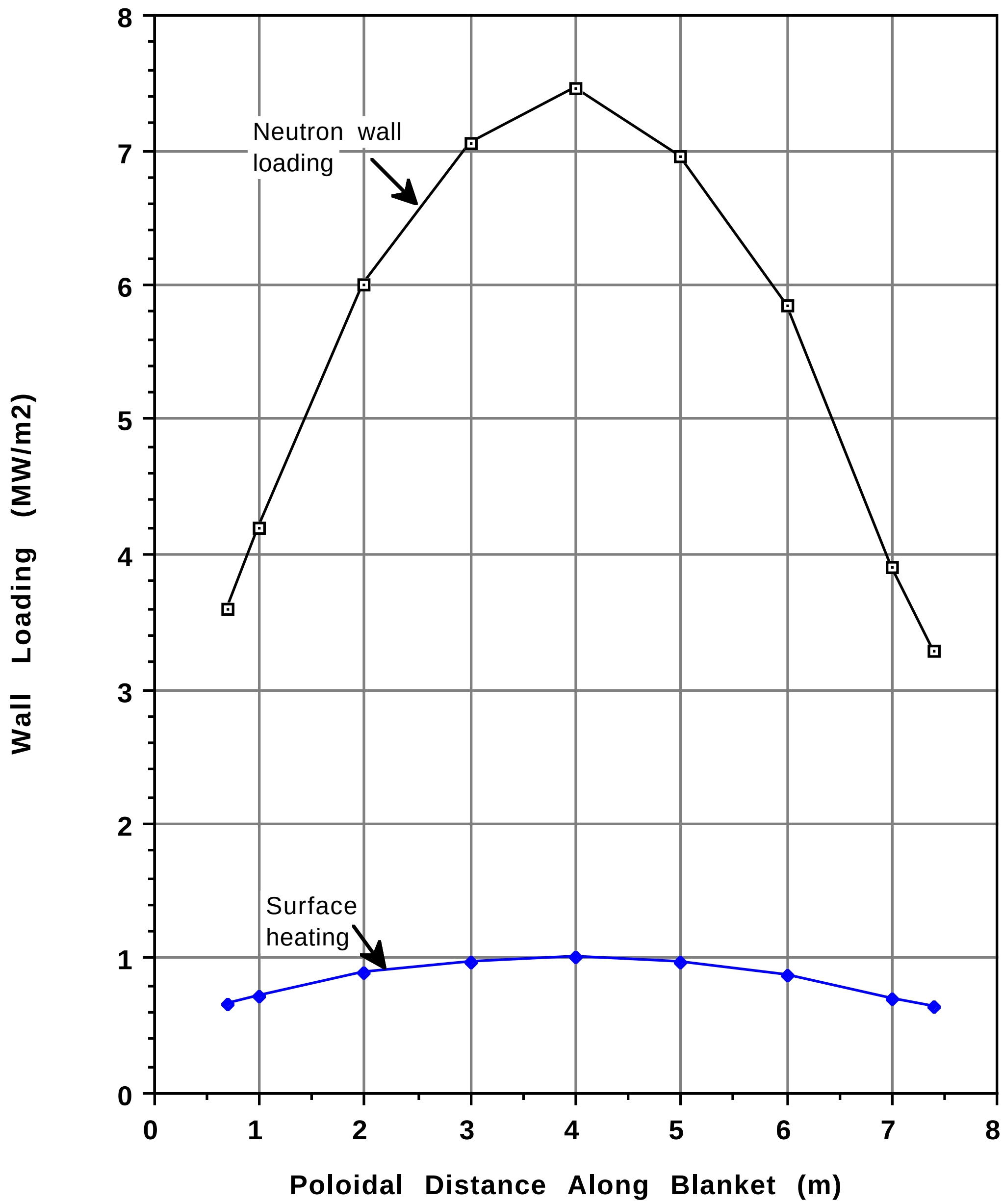

Operating Temperature of Spiral Blanket
at 10 MW/m2 NWL
Outer Surface
10MW/m2 NWL
Inner Surface
10MW/m2 NWL
Flibe Temp.
Avg.NWL 6.38MW/m2
Peak NWL 9.6MW/m2
Surf.Heat 15% of Avg.
NWL with peak. factor
of 1.3
Temperature (C)
Poloidal Distance (m)
820
800
780
760
740
720
700
680
660
640
620
600
580
560
540
520
500
0
1
2
3
4
5
6
7
8



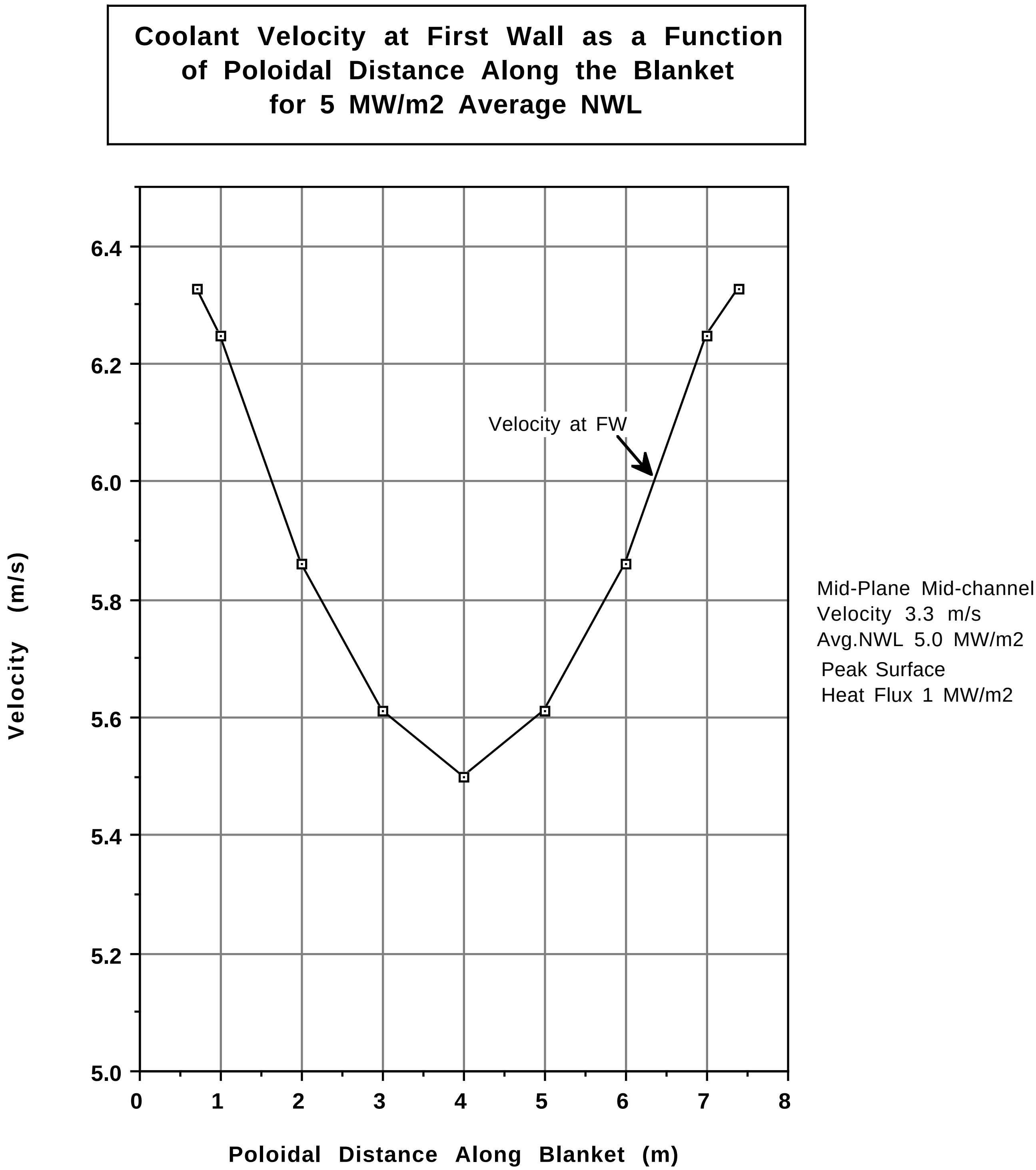
Poloidal NWL distribution and Surface heating as in ARIES-AT

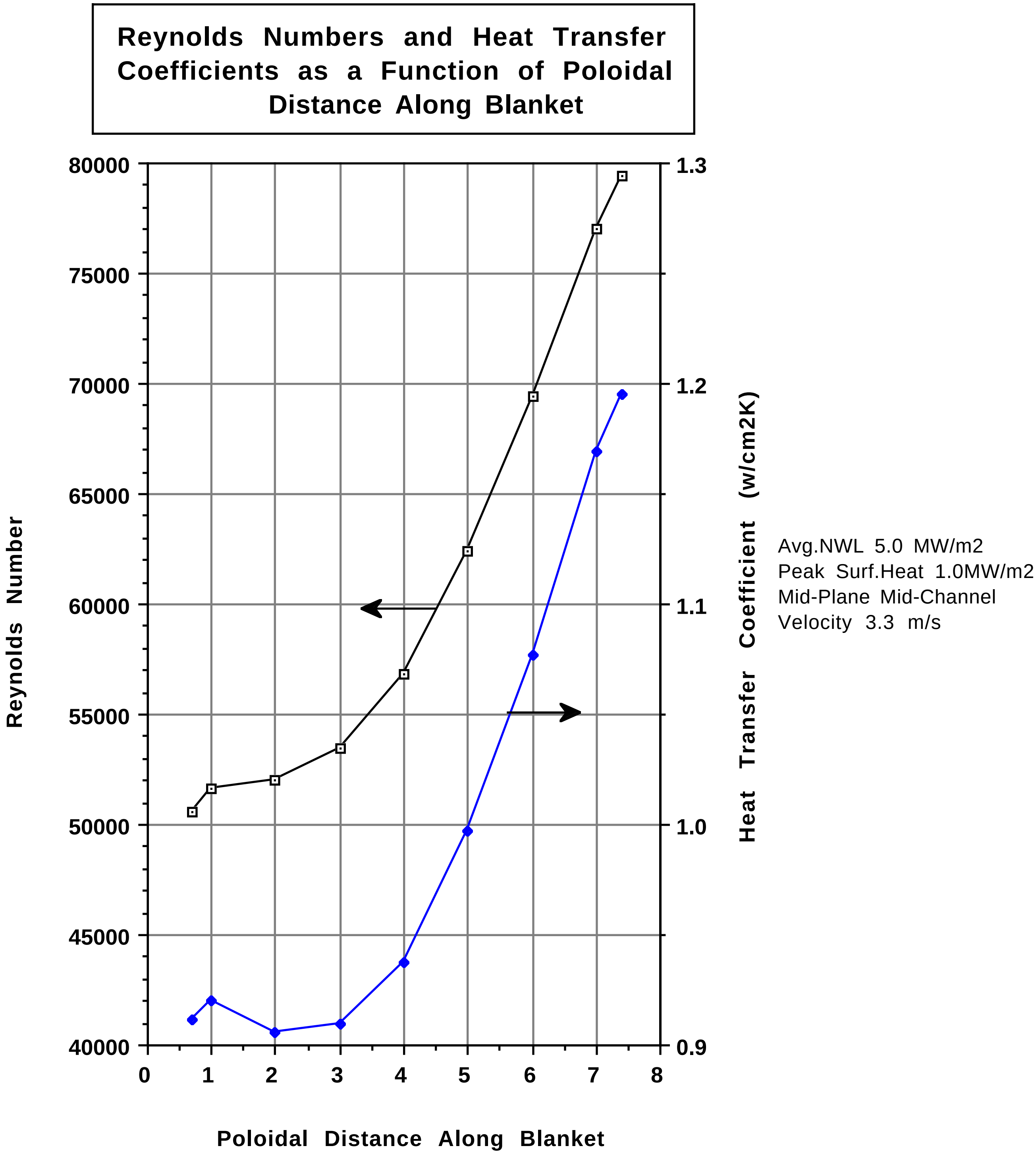
Mid-plane mid-channel velocity 3.3m/s

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



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


Coolant Velocity at First Wall as a Function of Poloidal Distance Along the Blanket for 5 MW/m2 Average NWL
Velocity (m/s)
6.4
6.2
6.0
5.8
5.6
5.4
5.2
5.0
0
1
2
3
4
5
6
7
8
Poloidal Distance Along Blanket (m)
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
Reynolds Number
Heat Transfer Coefficient (w/cm2K)
Poloidal Distance Along Blanket
80000
75000
70000
65000
60000
55000
50000
45000
40000
1.3
1.2
1.1
1.0
0.9
0
1
2
3
4
5
6
7
8
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/m^2 peak neutron wall loading:
  - Peak nuclear heating in FS FW 43 W/cm^3
  - Peak nuclear heating in spiral blanket 39 W/cm^3
  - Average nuclear heating in spiral blanket 17 W/cm^3
  - 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/m^2 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}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}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

Stress Analysis of Spiral Blanket First Wall

By S. Majumdar (ANL)

1) <u>Spiral blanket (Igor's design)</u>

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.

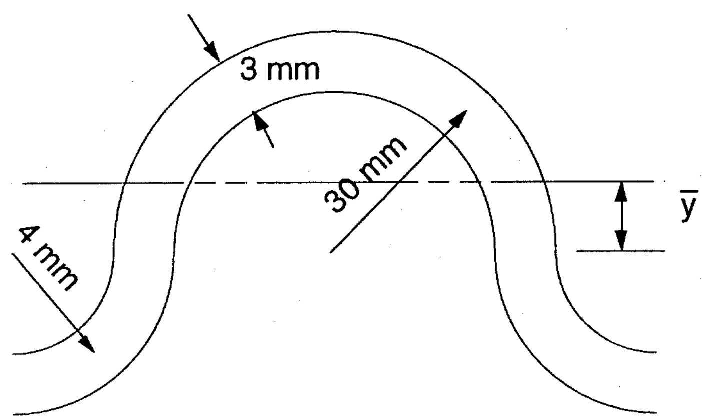


Figure 1. Corrugated spiral blanket first wall (Igor's design).

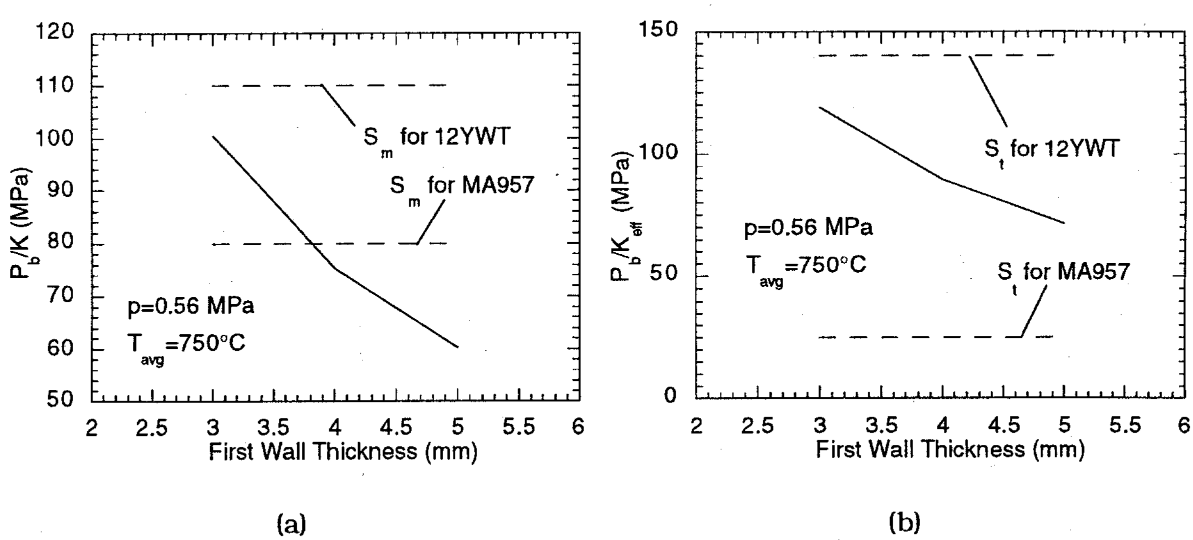


Figure 2. Variation of (a) modified primary bending (P_b/K) stresses and (b) modified primary bending stresses (P_b/K_{eff}) with first wall thickness for Igor's spiral blanket design.

Ranges for Calculating Coefficients of Resistance in Curved Flow Geometries

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

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

   $f = 20/Re\#^{0.65}(D_h/2R_o)^{0.175}$

2) $600 < Re\# \, (D_h/2R_o)^{0.5} < 1400$

   $f = 10.4/Re\#^{0.55}(D_h/2R_o)^{0.225}$

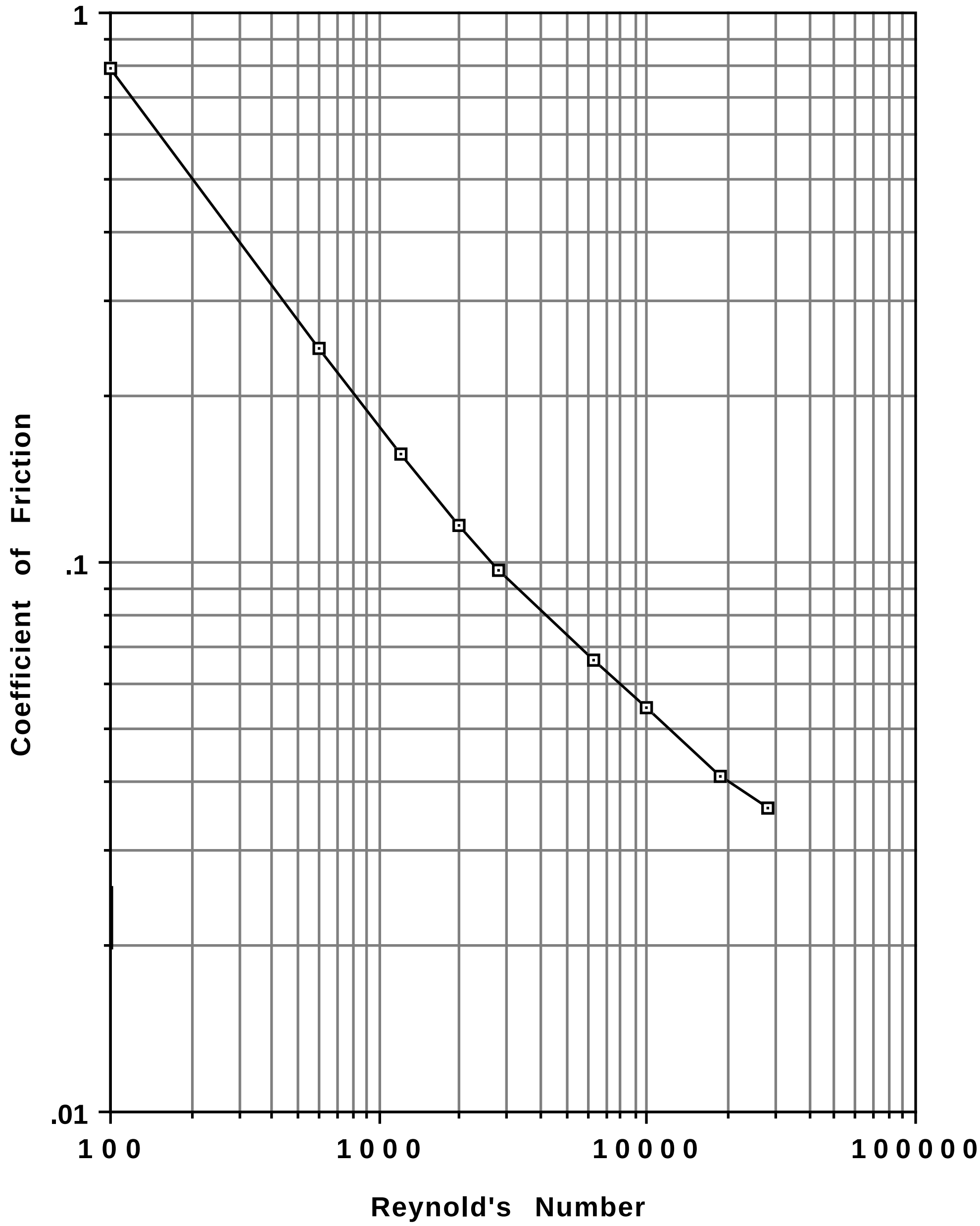
3) $1400 < Re\# \, (D_h/2R_o)^{0.5} < 5000$

   $f = 5/Re\#^{0.45}(D_h/2R_o)^{0.275}$

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

   $f = 2/Re\#^{0.35}(D_h/2R_o)^{0.32}$

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=17cm



Taken from Handbook of Hydraulic Resistance
I.E.Idel'chik

Pressure Drop in spiral blanket

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

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

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

$$Re = 28280$$

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

for $v = 3.0$ *m/s* $\Delta P = 0.496$ *MPa.*

for $v = 3.3$ *m/s* $\Delta P = 0.600$ *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/m^2.

•Coolant outlet temperature ranges from 600°C at 10 MW/m^2 nominal peak to 665°C at 5 MW/m^2 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.

<u>Possible issue</u>

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