Spiral Blanket: An Innovative Idea For Solid Wall Blankets With Potential For High Neutron Wall Loading

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SPIRAL BLANKET: AN INNOVATIVE IDEA FOR SOLID WALL BLANKETS WITH POTENTIAL FOR HIGH NEUTRON WALL LOADING

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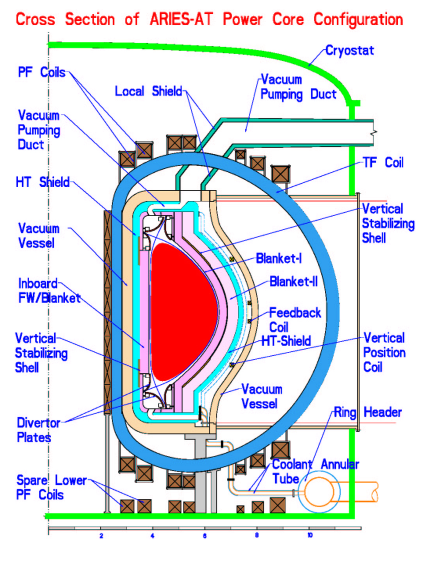
ABSTRACT

The Advanced Power Extraction (APEX) program is exploring concepts for blanket designs that can enhance the potential of fusion while using both liquid and solid walls. In that context, an innovative blanket design of dry solid wall configuration, with potential for high neutron wall loading is proposed here. The blanket utilizes nano-composited ferritic (NCF) steel structure which has an upper operating temperature of 800C. The cooling/breeding material is Flibe (Li_2BeF_4), a low viscosity version of molten salt which has a melting temperature of 465C and is compatible with ferritic steel up to 700C. In this design, the coolant travels within a module on spiral discs from the bottom to the top, such that all the coolant participates in dissipating the surface heat flux, allowing a higher incidence of wall loading. The centrifugal effect of the liquid flow around the discs accelerates the velocity at the first wall, improving the heat transfer while minimizing the pressure drop. An average neutron wall loading of 6.4 MW/m^2 is possible. The peak neutron wall loading is 9.6 MW/m^2 while the peak surface heat flux is 1.3 MW/m^2. The inlet Flibe temperature is 500C and the outlet, 600C. Assuming a supercritical steam power cycle, the conversion efficiency can approach 48%.

INTRODUCTION

The Advanced Power Extraction (APEX) program has been instituted by DOE-OFE for exploring methods of maximizing the neutron wall loading in fusion devices. The program covers liquid protected first walls (FW) and solid FW designs. Task IV of the program is exploring solid walls, and is where the present design has its origin. There have been many solid first wall designs proposed in the past, but they were all intended for specific neutron wall loads dictated by the physics of the device. This is the first time that effort has been expended to determine the limit that can be achieved with respect to neutron wall loading on a metallic solid first wall using relatively conventional materials. Although ferritic steels have been used in the nuclear industry for a long time, nano-composited ferritic (NCF) steels are newcomers. These materials, such as that designated 12YWT, derive their superior performance from the addition of small quantities of ceramic materials to the melt. While conventional ferritic steels are not recommended for temperatures above 550C, NCF steels retain their strength up to 800C. It has also been determined that Flibe (FLi_2BeF_4) is compatible with ferritic steels as long as the chemistry is kept in balance. The combination of the superior strength of NCF steel, and its compatibility with Flibe, opens up new possibilities for solid metallic FWs. Furthermore, the innovative design of the present blanket, using spiraling discs in the vertical direction within a module, takes advantage of two important aspects, namely the accelerated fluid velocity due to the centrifugal action of the flow at the FW and the uniform distribution of the flow around the module, allowing all the coolant to participate in dissipating the high surface heating. All this combines to make the Spiral Blanket uniquely suitable for high neutron wall loading.

Cross Section of ARIES-AT Used as Reference



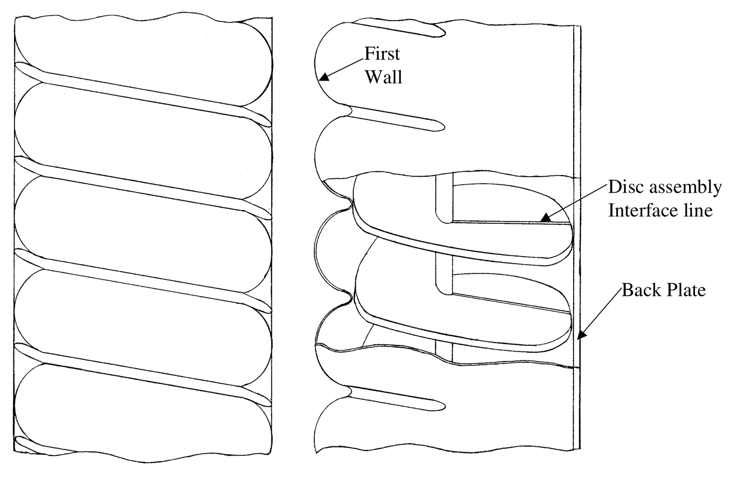
OVERALL GENERAL DESCRIPTION

- The dimensions for this study have been adopted from the ARIES-AT design study shown in the previous figure, from which the profiles of the neutron wall loading and the surface heating have been taken. Only the outboard blanket has been designed, since it has the highest neutron and surface heating.
- The area of an outboard module at mid-plane is 0.3 m x 0.3 m and the vertical extent is 8m. At the upper and lower extremities, the area is reduced to 0.3 m x 0.22 m to allow for the reduced radius.
- The heart of the design is a spiral consisting of discs oriented in the vertical direction within each module. The discs are near square at mid-plane and are near rectangular at the extremities. The discs are fabricated individually and are mounted on a shaft, with the mating interface between each disc located in the back of the module.
- The neutron multiplier is a Be pebble bed which is contained in each disc. Thus the discs consist of two perforated NCF half plates, an upper and a lower half, which when assembled enclose the Be balls. After the halves are joined together by diffusion bonding, the disc is filled with Be balls through a prepared hole in the flat surface at the interface between discs. The hole is then sealed with a plug. Space is provided at the upper surface of the disc to allow for Be swelling.
- The perforated plates of the discs allow Flibe to pass through the Be bed for cooling and for Be contact which is needed to keep the Flibe adequately supplied with Be to prevent corrosion of the steel.
- Figure 2 shows two views of a section of a module, a front view facing the plasma and a side view with a cut-away showing several discs. The lines in the back of the module show the interface between individual discs.
- The FW consists of semi-circularly shaped scallops progressing in the direction of flow. The discs come close to, but do not touch the junctions between the FW scallops. Coolant flow at the FW is smooth and unobstructed.

GENERAL DESCRIPTION (contd.)

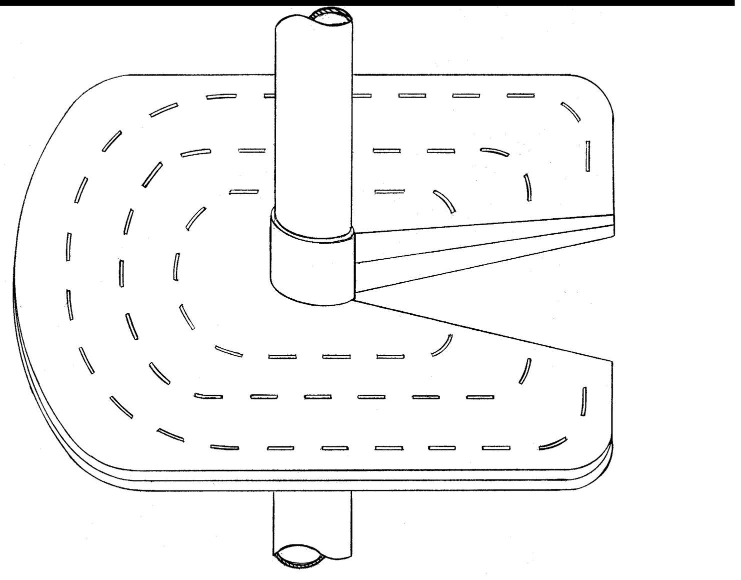
- The figure below shows a single disc mounted on a shaft. Note that the perforations are oriented in the direction of fluid flow in order to present the least resistance to the coolant. Each disc is then keyed to the shaft to prevent rotation or slippage during operation.
- The scallops at the FW perform several functions. They in effect reinforce the FW against internal pressure in the same way as corrugations reinforce corrugated roofing material. The scallops start in the center of the side walls and progress across the FW and all the way to the center of the opposite side wall. This design obviates the need for providing welded reinforcements across the FW.
- The orientation of the scallops is in the direction of fluid flow, providing a tube-like surface against which the flow is accelerated due to centrifugal action.
- The next figure shows a cut-away exposing the Be balls. Notice that the disc thickness tapers from 5.0 cm at the shaft to 1.0 cm at the FW. This allows a 20% Be volumetric quantity at 65% solid fraction to be included unobtrusively, with a minimum impact between the discs and the FW.
- The Flibe coolant circulates on the spiral discs from the bottom of the module to the top. The velocity varies from near zero at the shaft to maximum at the FW where it needed to produce a high heat transfer coefficient for dissipating the surface heating while keeping the pressure drop at a low value.

FRONT AND SIDE VIEWS OF A SECTION OF MODULE

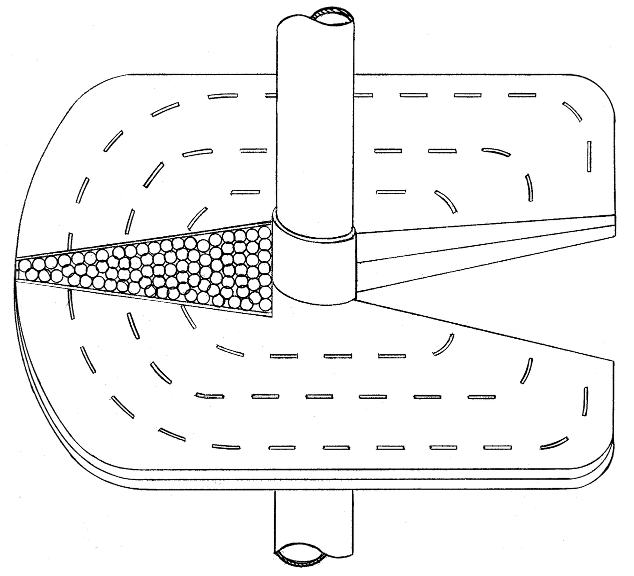


Front View Facing Plasma   Side View With Cutaway

A NEAR SQUARE DISC ASSEMBLED ON A SHAFT



A DISC WITH A CUT-AWAY EXPOSING Be BALLS



PHYSICAL PARAMETERS OF THE SPIRAL BLANKET

Poloidal height along module (m)	6.7
Mid-plane module cross-section (cm x cm)	30 x 30
Cross-section at extremities (cm x cm)	30 x 23
First wall thickness (cm)	0.3
Number of discs	70
Disc thickness at first wall (cm)	1.0
Disc thickness at shaft (cm)	5.0
Disc cladding thickness (cm)	0.2
Dimension of a scallop (cm)	6.7
Channel height at first wall (cm)	6.7
Channel height at shaft (cm)	4.2
Average fluid path length (m)	32.9
Hydraulic diameter of channel (cm)	8.6
Steel shaft diameter (cm)	3.0
Be pebble bed packing fraction (%)	65

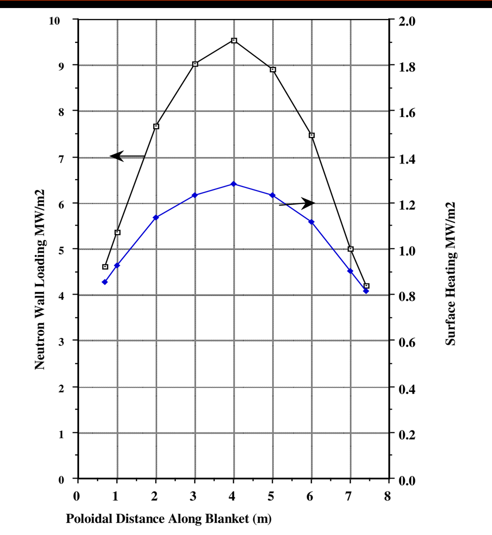
THERMAL HYDRAULICS OF SPIRAL BLANKET

- The thermal hydraulics of the SPIRAL blanket have been predicated on maximizing the neutron wall loading and the consequent surface heating, while achieving coolant temperatures which yield a high conversion efficiency.
- The design has all the coolant volumetric flow participate in the heat dissipation at the FW and absorbing the nuclear heating in the rest of the module. Since the coolant rotates on the discs from the back to the front and to the back again, the temperature of a module in the radial direction is uniform, but increases in the vertical direction, from the bottom to the top.
- The coolant enters each module on the bottom at 500C, then circulates on the spiral discs picking up temperature in the vertical direction, then exits the module at the top. In the demonstration example at an average neutron wall loading of 6.4 MW/m^2, the exit temperature from the primary module is 590C.
- The coolant picks up another 10C in the secondary module located immediately behind the primary, exiting the reactor at 600C and is piped to the steam generator.
- The coolant flow at the FW is horizontal, meaning it is parallel to the dominant toroidal field, and therefore not subjected to MHD effects. Even though Flibe is a poor electrical conductor, if the flow cuts across magnetic field lines, and is contained in metallic channels, there will be MHD effects which compromise heat transfer and increase pressure drop.
- At the 6.4 MW/m^2 average neutron wall loading, the maximum external NCF steel temperature is 800C and the maximum interface temperature with Flibe is 690C.

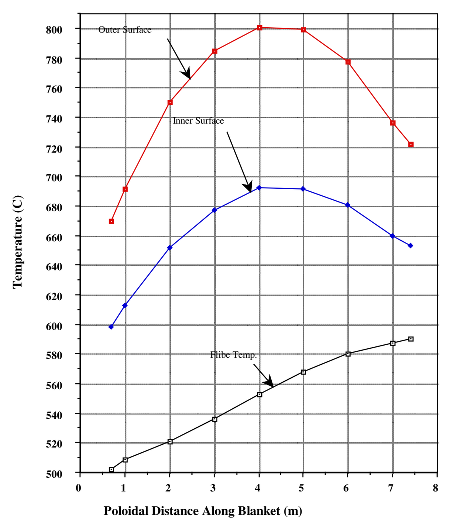
Thermal Hydraulics Parameters for the Case of an Average Neutron Wall Loading of 6.4 MW/m^2 and a Peak Surface Heating of 1.3 MW/m^2

Maximum NWL (MW/m^2)	9.54
Average NWL (MW/m^2)	6.4
Maximum surface heating (MW/m^2)	1.3
Mid-plane, mid-channel velocity (m/s)	3.3
Range of velocities at FW (m/s)	5.5-6.3
Coolant inlet temperature (C)	500
Coolant exit temp. from module (C)	590
Coolant temperature to power cycle (C)	600
Maximum steel temperature (C)	800
Maximum interface temp. with Flibe (C)	694
Pressure drop through module (MPa)	0.56

Poloidal Distribution of Neutron Wall Loading and Surface Heating in the Case of 6.4 MW/m^2 Average NWL

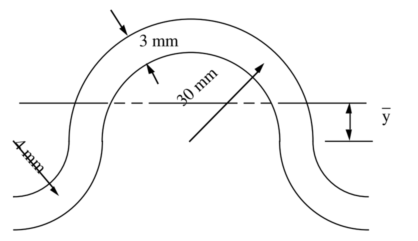


Variation of Inner and Outer First Wall Surface, and Flibe Temperatures as Functions of Poloidal Distance Along the Blanket for an Average Neutron Wall Loading of 6.4 MW/m^2

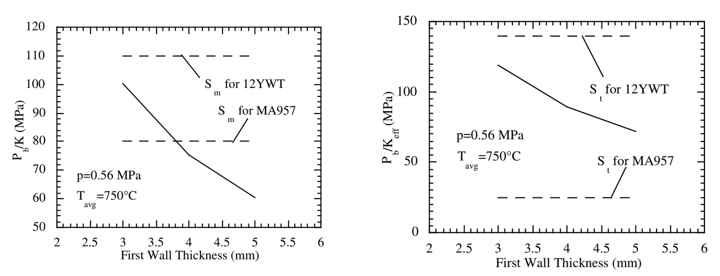


PRELIMINARY STRESS ANALYSIS PERFORMED BY SAURIN MAJUMDAR (ANL)

- The results of a preliminary stress analysis shown below. The corrugated spiral FW is modeled with a toroidal span of 30 cm, the width of a module at mid-plane and is analyzed using beam theory.
- The bending shape factor K for the section is 1.47. The graphs show the variation of P_b/K and P_b/K_{eff} for a 0.3 cm thick FW, a pressure of 0.56 MPa and a temperature of 750C. This is the maximum FW temperature averaging the inside and outside temperatures.
- The left side graph gives the modified primary bending stresses S_m. The right side graph gives S_t, which includes time effects for 3 FPY of operation.
- The graphs are shown for two NCF materials, 12YWT and MA957.
- It is clear that for a 0.3 cm thick FW at 0.56 MPa and 750C, 12YWT satisfies both S_m and S_t with margin to spare. However, MA957 does not.
- This analysis proves that a corrugated wall as used in the spiral blanket can reinforce the FW against internal pressure without the addition of reinforcing beams which will require welding at the FW and compromise its strength.



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

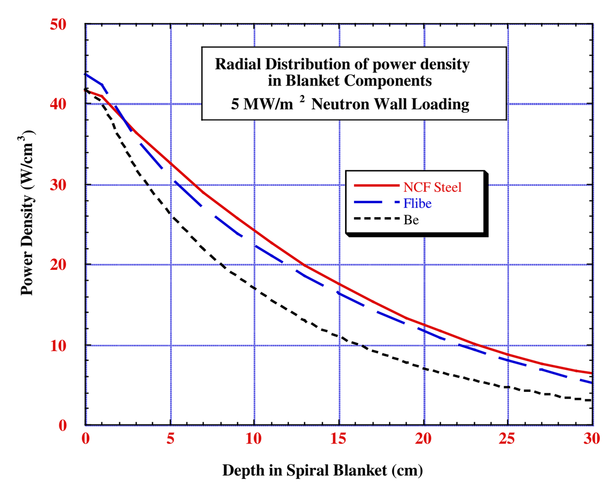


Variation of (a) modified primary bending (P_b/K) stresses and (b) modified primary bending stresses (P_b/K_{eff}) with first wall thickness for Igor's spiral blanket design.

NEUTRONICS FEATURES

- The model includes a 30 cm thick spiral blanket composed of 74.4% Flibe, 18.67% Be and 6.93% NCF structure. A 45 cm thick secondary breeding blanket is included at the back of the outboard side with 95% Flibe and 5% NCF structure
- The local tritium breeding ratio (TBR) is 1.16 in the inboard side using natural Li. The overall TBR is 1.33 excluding tritium bred in the diverter region that could add 0.05 to the overall TBR.
- The energy multiplication (M) is 1.12 in the spiral blanket, and when the secondary blanket is included, rises to 1.26.
- The nuclear heating in the various constituents of the spiral blanket as functions of blanket depth are shown in the Figure below, normalized to a neutron wall loading of 5 MW/m^2. Poloidal variation of power density was determined by scaling the results with the poloidal distribution of the neutron wall loading.
- The peak dpa rate in the FW is 58 dpa/FPY. Using 200 dpa as the limit gives the FW a lifetime of 3.4 FPY. The peak dpa in the secondary blanket is only 3.2 dpa/FPY, implying that it can be a lifetime component.
- The peak He production in the Be is 18,400 appm/FPY. This corresponds to a total He production that uses 6% of the Be atoms at the spiral blanket end of life. This is an important parameter for assessing irradiation swelling in the Be.

RADIAL DISTRIBUTION OF POWER DENSITY IN THE SPIRAL BLANKET CONSTITUENTS



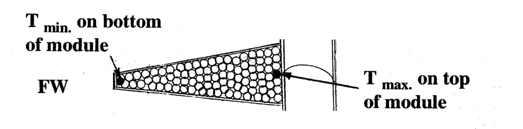
TRITIUM PRODUCTION IN Be

- Tritium production in the Be pebble bed has been calculated for the expected life of the spiral blanket of 3.4 FPY.
- The total spiral blanket volume of 104.2 m^3 results in a total Be inventory of 36 tonnes.
- The total tritium production in this Be volume in 3.4 FPY is 1.9 kg. This is comparatively lower than in typical solid breeder blankets, due to the smaller Be inventory and distribution of the Be over the blanket thickness resulting in a lower average neutron flux.
- The actual tritium inventory will be lower than 1.9 kg because of the diffusion of the tritium from the Be. Based on available data, the temperatures at which most of the Be is released is in the range of 500-700C depending on the density and neutron fluence. Lower density and higher fluence result in lower release temperatures.
- Estimated Be temperatures in the spiral blanket range from 580-770C in the bottom first disc and 680-870C in the upper last disc.
- Therefore, it is expected that the Be inventory in the spiral blanket is not an issue

FABRICATION

- One of the issues with NCF steels has to do with fabrication, in particular joining. So far the only joining method that seems to work well is diffusion bonding. Fortunately the spiral blanket has been configured to be fabricated using forming and diffusion bonding.
- The whole front end of the module is formed from one piece of NCF steel sheet, including the FW scallops and the side walls, but without the back wall. Inlet and outlet coolant holes are drawn out with a lip for diffusion bonding to coolant tubes.
- Small side clamps are diffusion bonded on the inside of the side walls for securing the location of the discs and stabilizing them during operation.
- An assembly of discs (see disc fabrication explained earlier) mounted on the shaft is inserted into the module from the back and secured to the side clamps.
- By shaping the outer edge of the back side with a lip, the rear closure plate can be diffusion bonded to the outer edge lip. Clamps are used to apply pressure to the lip while heating tapes provide the temperature.
- Once the module is completely assembled, it is leak checked, cleaned and is ready for insertion into the power core of the reactor.

Estimated Be Pebble Bed Temperature



Assumption: Cooling is by conduction through the bed only

k_{Be}	=	90 w/mK	fraction = 0.65
k_{Flibe}	=	1 w/mK	fraction = 0.35
$k_{eff.bed}$	=	30 w/mK	Deissler Boegli method
$k_{ferr. St.}$	=	28 w/mK	

Average nuclear heating near shaft = 17 w/cm^3
Disc thickness near shaft = 5.0 cm
Heat transfer coeff. near shaft = 0.5 w/cm^2K
Be T_{max} is near shaft at top of module = 870C

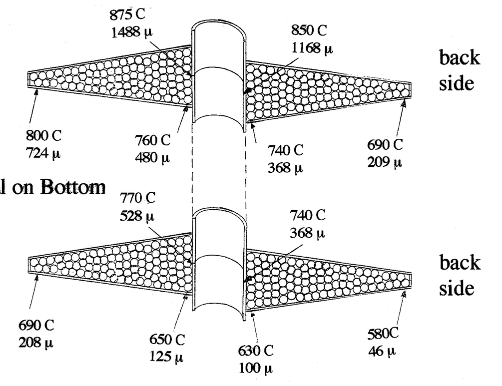
Peak nuclear heating near FW = 39 w/cm^3
Disc thickness near FW = 1.0 cm
Heat transfer coeff. near FW = 0.9 w/cm^2K
Be T_{min} is near FW at bottom of module = 690C

Compatibility of Be with NCF Steel in Spiral Blanket

- Be temperature was estimated where it is in contact with NCF steel. The lowest temperature is on the bottom of the first disc close to the shaft and is 650C. The highest temperature is in the last disc close to the shaft and is 875C.
- The calculated thickness of the inter-metallic superficial layer is given in microns for a period of ~26,000 hours (3FPY)
- The thickness of the perforated discs enclosing the Be balls is 0.2 cm and the thickness of the shaft tube wall is 0.5 cm.
- The figure below gives the temperatures of the Be balls in contact with the NCF steel and the thickness of the superficial inter-metallic layer formed.
- The largest inter-metallic layer occurs at the highest Be ball temperature of 875C where it is in contact with the shaft. This layer is ~ 1500 microns while the shaft thickness is 5000 microns.
- It can be concluded that the issue of Be/NCF steel compatibility appears to be manageable.

Figure Showing the Temperature of Be Balls in Contact with NCF Steel and the Thickness of the Inter-Metallic Superficial Layer

Estimated Be temperatures in contact with NCF steel:



CONCLUSIONS

- A new and innovative blanket design has been configured for a dry solid FW concept within the auspices of the APEX study. The blanket uses NCF steel as the structure and Flibe as the coolant/breeder.
- The blanket modules are equipped with spiral discs which make the coolant to rotate accelerating the flow near the FW due to centrifugal action. This results in good heat transfer while minimizing pressure drop.
- Thermal hydraulics shows that the blanket is capable of an average NWL of 6.4 MW/m^2 and a peak NWL of 9.5 MW/m^2. Peak surface heating is 1.3 MW/m^2. The maximum external FW temperature is 800C and the interface temperature with Flibe is < 700C.
- The pressure drop is a modest 0.56 MPa and the resulting stresses for a 0.3 cm FW are well within the range for the 12YWT NCF steel after 3 FPY of operation.
- Neutronics analysis shows an overall TBR of 1.33 using natural Li and the energy multiplication M is 1.26.
- The maximum tritium inventory in the Be is 1.9 kg and when diffusion is assumed will be much lower.
- The issue of Be/NCF steel compatibility is shown to be manageable.
- Fabrication of the blanket entails forming and diffusion bonding only, both of which have been demonstrated to be viable for NCF steel.
- A Flibe outlet temperature of 600C is capable of a thermal efficiency ~ 48% assuming a supercritical steam cycle with a double walled heat exchanger.