Engineering Description of a Solid First Wall Blanket Based on Advanced Ferritic Steel and Re-circulating Flibe

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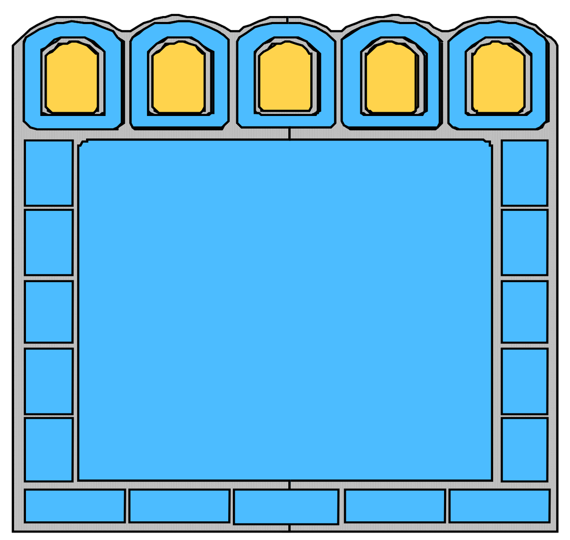
ABSTRACT

A solid wall blanket utilizing advanced ferritic steel and re-circulating Flibe has been scoped out under the Advanced Power Extraction (APEX) Program. This paper describes the engineering aspects of the design. The new alloy is the nano-composited ferritic (NCF) steel, 12YWT, the breeding/cooling material is Flibe (Li_2BeF_4) and the neutron multiplier is Lead. The coolant is re-circulated through the blanket to achieve an outlet temperature of 681°C permitting the use of a Brayton Power Cycle with an efficiency of 47%. Material issues, structural analysis, fabrication aspects and coolant circuits are covered.

Midplane cross-section of an outboard blanket module



GENERAL DESCRIPTION

- The structural material of the re-circulating blanket is the nano-composited ferritic steel 12YWT developed at ORNL.
- Each blanket module has five first wall (FW) channels followed by a box with side and back channels, surrounding the main large return channel.
- The FW channels have tubes containing molted lead which acts as a neutron multiplier. The coolant and breeding material is Flibe (Li_2BeF_4).
- The Flibe first flows vertically through the FW channels, then splits into two streams, the first returning through the side and back channels, and the second through the center channel.

GENERAL DESCRIPTION (Continued)

- The first stream goes to a mixing chamber, where it combines with coolant returning from the heat exchanger. This unique feature raises the temperature of the coolant exiting from the heat exchanger before it is returned to the FW channels of the blanket, to start another coolant cycle.
- The second stream flows down through the large back channel at a slow velocity, exiting the blanket at 681°C. This stream is then directed to the heat exchanger, where it exchanges heat with He gas used in a Brayton power cycle, achieving a conversion efficiency of 47%.
- Molten Pb is slowly circulated vertically through the tubes in the FW channels. The O_2 level in the Pb is closely monitored and controlled to insure that a stable oxide layer is formed and maintained on the inside of the steel tubes as a barrier for preventing corrosion.

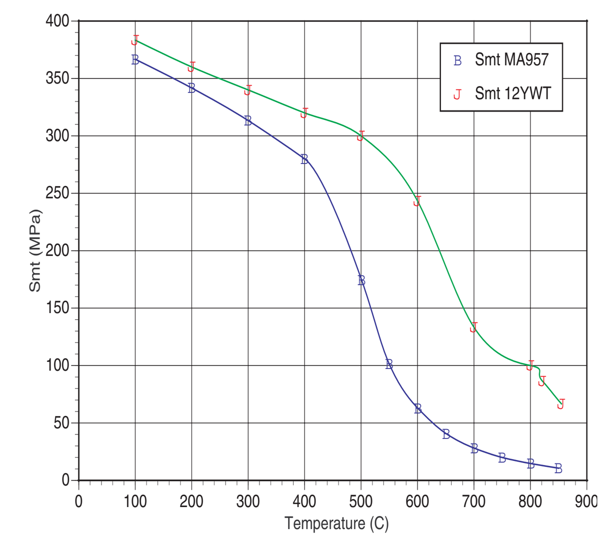
MATERIAL ISSUES

- Ferritic/martensitic steels have always been considered prime candidates for fusion reactors because of their lower swelling rates from radiation, higher thermal conductivity than austenitic steels and better high temperature strength.
- However these materials have an upper temperature limit of 550-600°C.
- One way suggested to increase this limit while retaining these inherent advantages, is by using oxide dispersion strengthened (ODS) steels.
- Elevated temperature strength in these steels is obtained through microstructures that contain a high density of small particles such as Y_2O_3, or TiO_2, dispersed in a ferritic matrix.
- One such material is 12YWT developed at ORNL. It has an upper temperature limit of 800°C and is compatible with Flibe up to 700°C.

MATERIAL ISSUES (continued)

- Next figure shows the combined time dependent and time independent stress intensity S_{mt} by taking the lower values of the respective curves.
- This figure shows the reason why fusion designers are eager to take advantage of this material and investigate the limits to which it can be used for improving the economics of fusion energy.
- Creep rupture tests for 12YWT have shown it to be vastly superior to other ODS steels.
- The maximum operating temperature of 800°C gets the coolant into a range where a He gas Brayton Cycle for power conversion can be used, which is both more economical, and safer from the standpoint of T_2 containment.

Calculated values of S_{mt} for 12YWT and MA957



MATERIALS COMPATIBILITY

- Two issues of compatibility are dominant in this design. They are compatibility of 12YWT with Flibe and that of 12YWT with Pb.
- Based on experiments at ORNL, the maximum temperature at which ODS ferritic steel can be used with Flibe is 700°C. This needs verification for 12YWT.
- Experiments in the USA and Russia have shown that compatibility of ferritic steels with Pb is determined by dissolution of structure by the molten Pb. This can be prevented by the formation of a stable adherent oxide film on the steel as a result of O_2 additions to the Pb. The window for maintaining this layer is very small and, requires a close control of the O_2 supply. The recommended temperature limit based on dynamic tests was 620°C. However, for semi-static rates, it was felt that this limit can be raised to 700°C.

STRESS ANALYSIS

- Heat conduction and stress analysis were carried out using the finite element program ABAQUS assuming a generalized plane strain condition.
- Temperatures and stresses in the blanket are predicted.
- Time-independent primary stresses allowable S_m and the time-dependent primary stresses allowable S_t are given.
- The primary stress limits for the membrane (P_m) and membrane plus bending (P_L+P_b) stresses are also listed.
- The design meets cycling ratcheting criteria as determined by the ITER Structural Design Criteria (ISDC).
- To satisfy the cyclic ratcheting criterion, X+Y=<1. Both stresses and ratcheting limits are satisfied in this design.

Summary of first wall temperatures and stresses

First wall location	Wall temperature (°C)		Primary stress intensity (MPa)		Secondary stress intensity (MPa) (Q)	S_m (MPa)	S_t (MPa)[a]
	Avg.	Peak	Memb. (P_m)	Memb.+ bending (P_L+P_b)			
Bottom	673	711	14	130	195	160	260
Midplane	709	758	10	90	283	125	240
Top	698	737	3	30	248	130	245

[a]Corresponds to two-year lifetime at average wall temperature.

First wall primary plus secondary stress limits

First wall location	Avg. wall temperature[a] (°C)	Yield stress (MPa)	$X = (P_L+P_b/K_t)/S_y$	$Y = Q/S_y$
Bottom	630	400	0.27	0.49
Midplane	650	350	0.20	0.80
Top	640	360	0.07	0.69

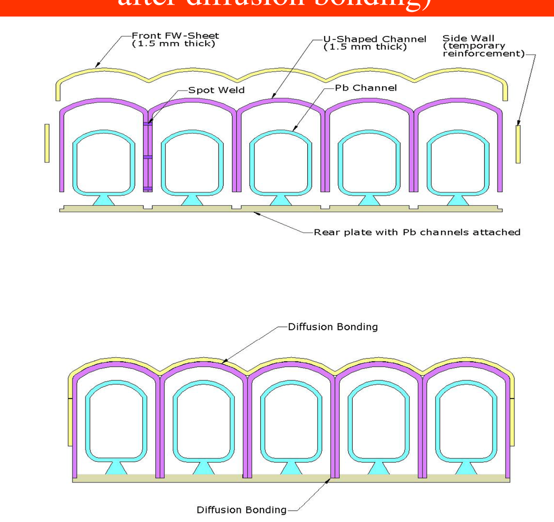
[a]Average temperature during plasma-on and plasma-off conditions

FABRICATION

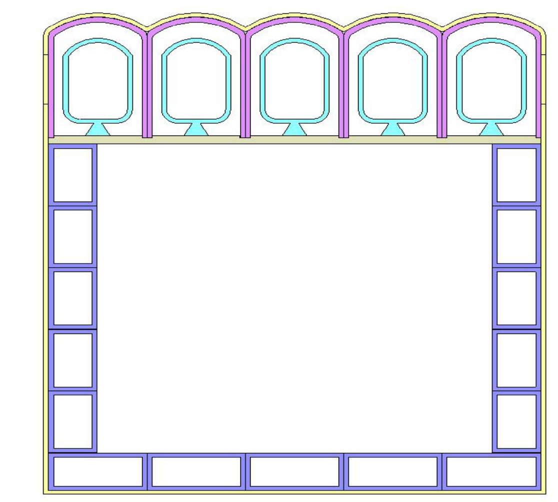
- A major disadvantage of using NCF steel is in fabrication.
- The only joining method that seems to work well is diffusion bonding.
- Conventional welding techniques have yielded joints that are inferior. For this reason, the methods that are investigated for this blanket are limited to diffusion bonding.
- Conventional welding is used only in places where temporary closures are needed to facilitate diffusion bonding.

Assembly sequence for fabricating FW channels

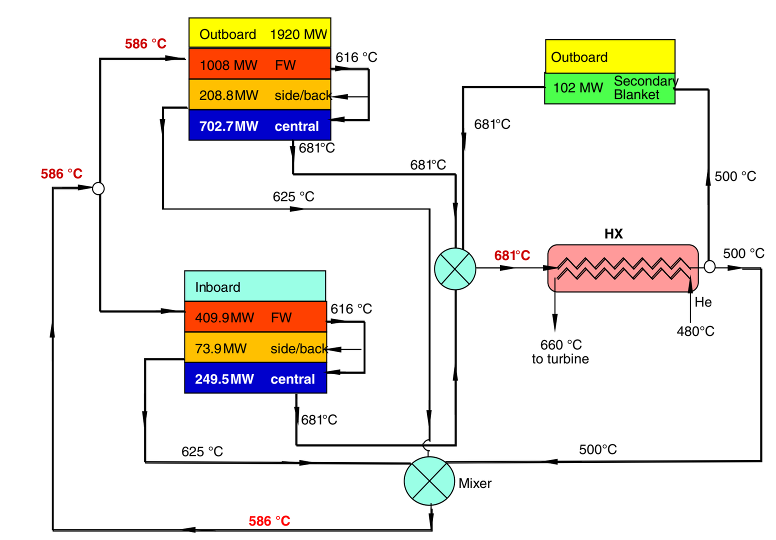
(Upper picture shows an exploded view and the lower an assembly after diffusion bonding)



A completed assembly of an outboard module at mid-plane



Fluid routing in re-circulating blanket



SUMMARY AND CONCLUSIONS

- A description of the geometric and engineering aspects, and preliminary stress analysis of the re-circulating blanket are presented.
- Time-depended and time-independent primary stresses, as well as primary and secondary stress limits are satisfied at all points in the blanket.
- Materials, and materials compatibility issues are addressed and solutions offered.
- Fabrication possibilities are presented and a coolant circuit is shown.
- Even though this blanket is somewhat complicated, its forward looking aims (e.g., maximizing nuclear parameters to achieve high conversion efficiency) are well worth striving for.