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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 and the breeding/cooling material is Flibe (Li_2BeF_4). The blanket has a solid first wall, but has an innovative coolant scheme, which allows part of the cooling fluid to be re-circulated to enhance the outlet temperature and thus improve the power cycle efficiency. Another innovation is the use of Pb as a neutron multiplier. The coolant outlet temperature is 681°C allowing a conversion efficiency of 47%. Material issues, structural analysis, fabrication aspects and coolant circuits are covered.**

I. Introduction

The Advanced Power Extraction (APEX) [1] program has been investigating innovative schemes for improving the prospects of fusion reactors as power producers. Among these schemes are liquid walls and solid walls. The present design utilizes a solid first wall made from the nano-composited ferritic steel 12YWT developed at ORNL [2]. This material has a maximum operating temperature of 800°C and an interface temperature with Flibe (Li_2BeF_4) of 700°C. Besides the use of an advanced structural material, the present design has two significant innovations. The first is a coolant scheme which allows a fraction of the fluid to be re-circulated within the blanket, thus achieving a He gas Brayton power cycle efficiency of 47%. The second is the use of Pb as the neutron multiplier. Because joining NCF steel is still not well developed, it is recommended that fabrication of the blanket be limited to diffusion bonding. The coolant pipes outside the vacuum vessel are combined duplex and triplex assemblies, thus limiting heat losses and preventing tritium diffusion from the pipes into the environment. This paper covers material and fabrication issues, structural analysis, and the coolant circuits of re-circulating blanket.

II. Description

Figure 1 is a midplane cross section of an outboard blanket module. The first wall (FW) is shown as a sheet of five scallops facing the plasma with five coolant channels behind them. The FW assembly is attached to the remaining blanket consisting of a box with channels on the sides and back, surrounding a large channel in the middle. At midplane, the outboard module is 30 cm wide and 30 cm deep; however, at the extremities, the width is reduced to 23 cm, but the depth is the same, reflecting the curving banana shape of the outboard module. The inboard modules are straight in the vertical direction and maintain the same dimensions throughout. Each of the FW channels contains a tube filled with molten Pb which acts as the neutron multiplier. The coolant traverses the FW channels vertically in the poloidal direction, flowing in the spaces surrounding the Pb tubes, then divides into two streams, one going through the rectangular side and back channels attached to the rear box, and the second going through the large central channel. In both cases the return flow is in the poloidal direction from top to bottom. The stream going through the side and back channels goes to a mixing chamber where it combines with the coolant returning from the heat exchanger. This mixing raises the temperature of the coolant stream from the heat exchanger, allowing it to return to the blanket at a higher temperature. The Pb tubes are fed through the bottom of the module and have the molten Pb moving in a semi-static mode for control of the oxide layer needed to prevent the corrosion of the steel by the Pb.

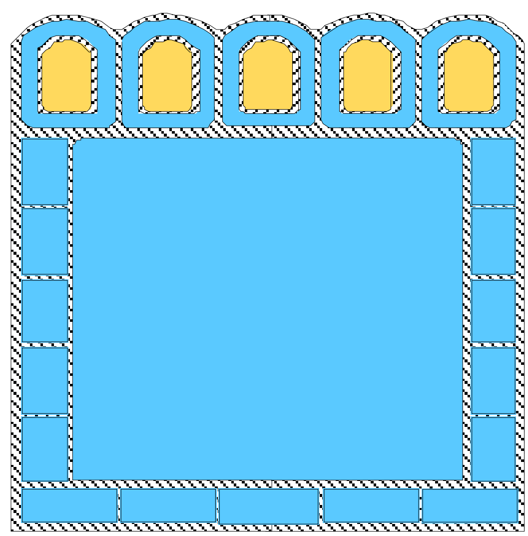

Fig. 1. Midplane cross section of outboard module.

III. Material Issues

Fusion reactor designers have been struggling to find the right materials, or the right material combinations for the design of the FW and blanket. There are so many singular concerns to be considered: physical properties, activation, radiation damage, upper temperature limits, thermal properties, electrical properties, corrosion, compatibility with coolants and neutron multipliers, and finally, MHD effects. Several of these issues are addressed in this paper.

Ferritic/martensitic steels have always been considered prime candidates for fusion 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 maintaining the inherent advantages of these materials 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 of Y_2O_3 or TiO_2 dispersed in a ferritic matrix. One such material being developed by ORNL is designated 12YWT, and is the one proposed for use in the present design [2]. This material has an upper temperature limit of 800°C and is compatible with Flibe up to 700°C [3].

Figure 2 shows the combined time independent and time dependent stress intensity S_{mt} by taking the lower values of the respective curves. This figure shows the reason why fusion reactor designers are eager to take advantage of this material and to investigate the limits to which it can be used for improving the economics of fusion energy. Creep strength of the material is another important criterion in selecting the structural material. Creep rupture tests for 12YWT have shown it to be vastly superior to other ODS steels [3]. Finally, 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 consideration of T_2 containment.

IV. Material Compatibility

Two issues of compatibility are predominant in this design. They are compatibility of 12YWT with Flibe and with Pb. The data on Flibe is from tests on conventional or reduced activity ferritic steel, derived from the assumption that minor additions of Ytria would have no effect on corrosion. Based on experiments at ORNL [3] the maximum temperature at which ODS ferritic steel can be used with Flibe was set at 700°C. This value will have to be verified with tests on 12YWT.

There is much more data on the compatibility of ferritic steel with Pb. For pure Pb and lead-bismuth, the primary corrosion mechanism is dissolution of the structural material. This can be prevented by the formation of an adherent oxide film, which forms and remains stable as a result of oxygen addition to the molten Pb. This approach has been taken by the Russians in their investigation of reactors using molten Pb in their submarines. The window for maintaining this layer is very small and, therefore, requires a close control of the O_2 supply. The recommended temperature limit based on dynamic corrosion tests was set at 620°C. However, since the Pb in this design is circulated at a semi-static rate, it was felt that 700°C might be acceptable [5]. This also needs experimental verification.

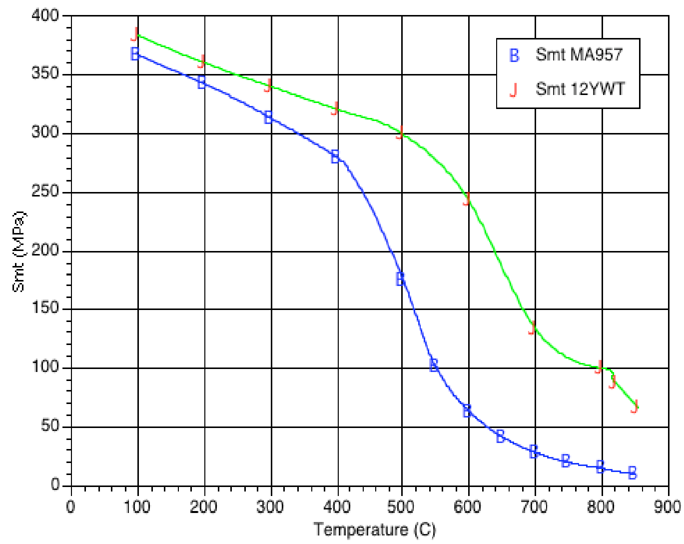

Fig. 2. Calculated values of S_{mt} for MA957 and 12YWT.

V. Stress Analysis

Heat conduction and stress analysis were carried out for this blanket design using the finite element program ABAQUS [6]. The reference cross-section in Fig. 1 was used and the stress analysis was conducted with the generalized plane strain assumption. Table I contains a summary of the temperatures and stresses in the blanket. The last two columns contain the time-independent primary stress allowable S_m and the time-dependent primary stress allowable S_t. The primary stress limits for the membrane (P_m) and membrane plus bending (P_L+P_b) are also listed. Table I shows that the stresses in the blanket at the bottom, midplane and top are within the prescribed limits.

Table II shows that the design also meets cycling ratcheting criteria. A simple but conservative rule for meeting the primary plus secondary stress limit for cyclic ratcheting is the A2 test of the ITER Structural Design Criteria (ISDC) [4]. This rule defines two factors, X and Y, in which X is the ratio of the membrane plus bending stress (modified by the shape factor K_t) to S_y, the stress at the average temperature of the section during the secondary stress cycle, and Y is the ratio of Q, the secondary stress intensity range during the cycle to S_y. To satisfy the cyclic ratcheting criterion, $X + Y \leq 1$. Table II shows that this criterion is satisfied for all FW locations.

Table I. 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]
	Average	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.

Table II. 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.

VI. FABRICATION

A major disadvantage of using NCF steel is in fabrication. The only joining method that seems to work well is diffusion bonding or hipping. Conventional welding techniques, such as MIG, TIG or plasma has yielded joints that are inferior. For this reason, the methods that are investigated for this blanket are being limited to diffusion bonding. Conventional welding is used only in places where temporary closures are required in order to facilitate diffusion bonding. Figure 3 shows an assembly sequence for fabricating FW cooling channels. The upper figure shows an exploded view with only the FW U channels temporarily spot-welded and the Pb channels welded to the rear plate. The bottom figure shows the assembly diffusion bonded together. The front FW sheet is diffusion bonded to the FW channels sealing off the spaces at the interface between the channels. The channel side walls, which were originally spot-welded together, are now diffusion bonded and the ends of the side walls are bonded to the rear plate. Figure 4 shows a completed assembly as it appears at the midplane in which the FW channels are bonded to the rear box.

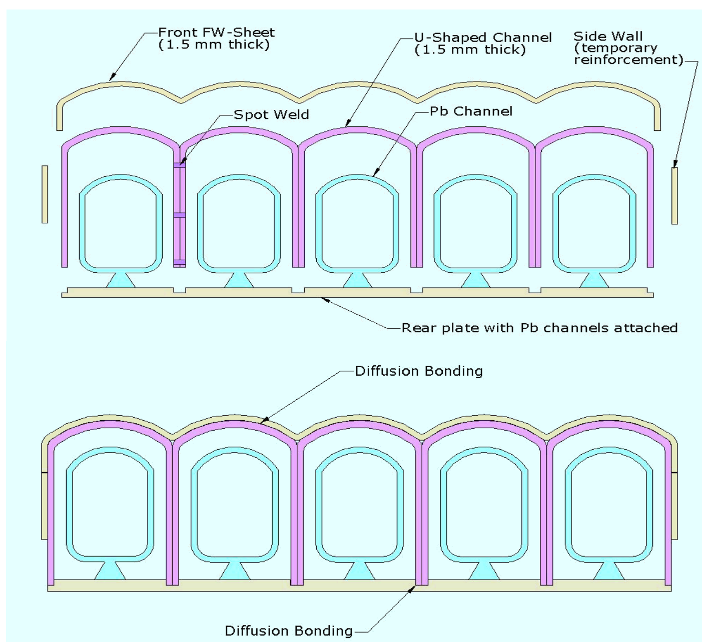

Fig. 3. Upper picture shows an exploded view and lower picture shows an assembly after bonding.

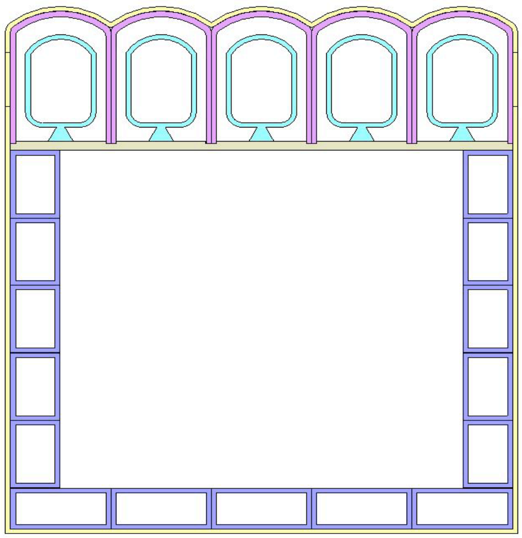

Fig. 4. A complete assembly of a blanket module.

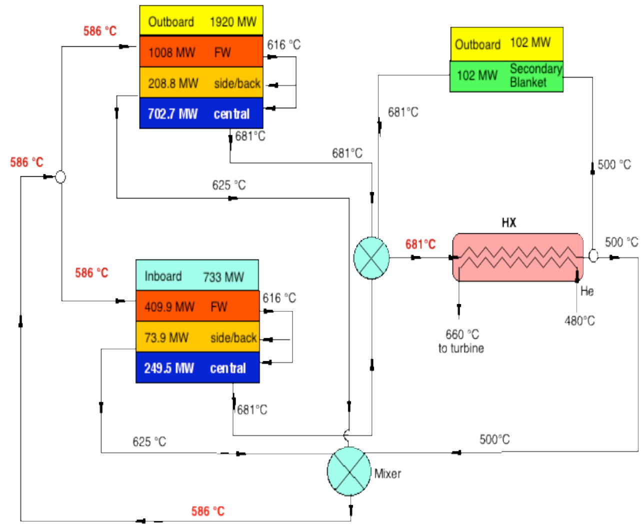

Fig. 5. Fluid routing in re-circulating blanket.

VII. Fluid Circuits

The re-circulating blanket has a complicated fluid circuitry, deriving from the fact that it maximizes the coolant temperature in order to achieve higher power cycle efficiency. The coolant outflow from the blanket is divided into two streams, one feeding the heat exchanger, and the other going to a mixer where it is combined with fluid returning from the heat exchanger. Figure 5 shows a coolant at a temperature of 681°C being delivered to the heat exchanger. The 500°C coolant, returning from the heat exchanger, mixes with the 625°C coolant coming from the side and back channels of the rear part of the blanket. The resulting coolant, at 586°C, is supplied to the FW channels of both inboard and outboard blankets. This pre-heating feature makes it possible to achieve the 681°C coolant outlet temperature going to the heat exchanger. Under those conditions, it is possible to use a He gas Brayton cycle for power conversion, at an efficiency of 47%.

In an effort to reduce heat losses from the pipes, duplex and triplex pipe arrangements are used. The inlet and outlet coolant connections to each module are made with triplex tubes. The innermost pipe carries the hot coolant from the rear central channel, the intermediate pipe carries the return from the side and back channels, and the outermost tube carries the coolant supply for the FW channels. There are two other benefits of using this tube arrangement. Minor leaks between the two innermost pipes can be tolerated; therefore, only one seal has to be broken when a line is cut. The outer tube will be cut, but the two inner ones will have sliding joints. The second benefit is the fact that T_2 leaks between the hot pipes are better contained within the system.

VIII. Summary and Conclusions

A description of the geometric and engineering aspects, and preliminary stress analysis of the re-circulating blanket are presented. It is shown that the time dependent and time independent primary stresses as well as the primary and secondary stress limits are satisfied at all points in the blanket. Material, and material compatibility issues are addressed and solutions offered. Fabrication possibilities are presented and coolant circuits are presented. Even though the re-circulating solid wall blanket is somewhat complicated, its forward looking aims, that of maximizing nuclear parameters to achieve high conversion efficiency, are well worth striving for.

Acknowledgment

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References

[1] M. A. Abdou and the APEX Team. "On the Exploration of Innovative Concepts for Fusion Chamber Technology" Fusion Engineering & Design, 54, 181 (2000).

[2] R. L. Klueh, P. J. Maziasz, D. J. Larson, N. Nashimoto, L. Heatherly, M. K. Miller (ORNL), I-S. Kim and K. Miyahara (Nagoya University), "Microstructure and Mechanical Properties of Oxide Dispersion-Strengthened Steels", June 20, 2000, DOE/ER-0313/18.

[3] S. J. Zinkle, Private communication, 2001.

[4] ITER Structural Design Criteria for In-Vessel Components (ISDC), ITER IdoMSS74MA1 97-12-12 R0.2, 1998.

[5] A. Lopatkin, Personal communication, 2002.

[6] ABAQUS, Hibbit, Karlsson & Sorenson, Inc. 2002.