Mechanical Design of a Solid Breeder Blanket Canister for ITER

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1.INTRODUCTION

A helium-cooled solid breeder blanket design proposed as a conceptual design for ITER (International Thermonuclear Experimental Reactor) uses a pressurized canister approach, with an integrated first wall facing the plasma[1]. The canisters are structurally independent and are positioned side by side along the poloidal direction on the outboard of the reactor. The helium coolant in each canister comes in at the sides, flows along the first wall channel, enters the canister at the first wall and then flows over an array of solid breeder and multiplier rods before exiting at the back of the canister. The first wall serves as a pressure boundary and has to withstand the coolant pressure load and the thermal stresses from the temperature gradient across it. Based on maintenance and assembly considerations, each canister is 33cm wide and 1.2m long, and its depth is about 70cm[1]. The purpose of this paper is to optimize the shape of the canister and the required internal structural support based on maximizing the space utilization within the given stress constraints. This would potentially increase the blanket and reactor compactness and hence reduce the cost. However, this would also increase the structure volume fraction as compared to a semi-circular shape for example and would result in lower tritium breeding. The trade-off would then be between a design which maximize s space utilization and hence reduces the cost, and one which minimizes the structural volume fraction and hence increases the tritium breeding but which also minimizes space utilization.
It is clear that maximum space utilization is obtained with a rectangular box type canister. However, calculations indicate that the stress imposed on the first wall for this case is up to an order of magnitude over the allowable stress limit. On the other hand, a low stress can be achieved if a perfectly semi-circular geometry of the first wall is chosen. However, this results in minimum space utilization. Therefore the optimum space utilization design lies between these. The mechanical and thermal stresses were evaluated using a 3-dimensional finite element code, and, the canister shape was then optimized for given first wall coolant channel size and heat flux. After the design was specified, evaluation for its life time was performed based on 2-dimensional linear elastic fracture mechanics analysis.

2.OPTIMIZATION OF CANISTER SHAPE

2.1 Method

A schematic view of this canister is shown in Figure 1 while the major design parameters are listed in Table 1[1]. One of the design features is that the low temperature coolant flowing in the first wall channel is thermally insulated from the higher-temperature coolant flowing over the breeder and multiplier rods by a stagnant helium layer trapped within a porous mesh on the outside of the second wall (not shown in Fig. 1 for simplicity). The first and the second walls, forming the first wall coolant channel are connected to each other by several thin ribs. Since the stress induced by the coolant pressure is over the design limit when a rectangular shape is adopted for the canister first wall, two different cases are considered for the design optimization: elliptical shape and flat shape with round corners. For each design, three kinds of stresses were evaluated:(i)The mechanical stress along the hoop direction which is induced by the coolant pressure(see fig.2 (a) and (b)). This stress has the minimum value when a perfectly cylindrical geometry is used, and has the maximum value when a rectangular shape containment is considered. (ii)The mechanical stress along the longitudinal direction which is induced by the bending moment due to the effect of the two edges(see fig.2 (c)). The magnitude of this stress depends on the ratio of the spacing between successive ribs and the wall thickness. (iii)The third one is the thermal stress caused by the temperature gradient perpendicular to the wall. The tensile stress along the longitudinal direction induced by the coolant pressure can be neglected due to the small coolant channel width. In Fig.2, P_1 and P_2 are 1.5MPa and 1.4MPa respectively following the parameters listed in Table 1 of Ref.[1].

Case I: Elliptical shape canister

(1) Hoop stress induced by the coolant pressure

The maximum stress occurs at the center of the canister and is given by the following equation:

$$\sigma_\phi = \frac{P_2 R^2}{h\,(t_1+t_2)} \qquad (1)$$

where R is the major radius of the ellipse and is half of the width of the canister, h is the minor radius, and t_1 and t_2 are the first and second wall thicknesses, respectively. Note that the effect of the ribs on this stress is ignored, which is reasonable because of small curvature along the longitudinal direction.

(2) Bending stress induced by the longitudinal end effects

Since it is very difficult to estimate the exact value of this stress analytically because of the 3-dimensional effect, the present analysis introduces a modification factor, F, to simplify the calculation. It is assumed that the maximum bending stress evaluated from the one-dimensional equation for a rectangular channel can be applied through the following expression:

$$\sigma_b = F\,\frac{P\,l^2}{2\,t^2}$$

$$P=P_2,\ t=t_1 \text{ for first wall ; } P=P_1-P_2,\ t=t_2 \text{ for second wall} \qquad (2)$$

where l is the spacing between ribs, F is the modification factor and has a value between 0 and 1. The case of F=1 applies for a straight rectangular channel. The detailed description of the evaluation of F is given in Section 2.2.

(3)Thermal stress

The following expression is used to estimate the maximum value of this stress:

$$\sigma_t = \frac{E\,\alpha\,\Delta T}{2(1-\nu)},\quad \Delta T = \frac{q'' t_1}{k} \qquad (3)$$

where q" is an effective heat flux on the first wall which accounts for the effects of both the plasma heat flux and the neutron heat generation. Note that the plasma heat flux is generally substantially larger than the effective heat flux due to the neutron heat generation. For example, for the reference ITER case of Ref.[2], the plasma heat flux is 0.22MW/m^2 and the effective heat flux from the first wall neutron heat generation is about 0.05MW/m^2 for a first wall thickness of 5mm.

The design of the canister should satisfy the ASME Code criteria, which are:

For the first wall $\sigma_\phi + \sigma_b < \sigma_m$ (4)

$\sigma_\phi + \sigma_b + \sigma_t < 3\,\sigma_m$ (5)

For the second wall $\sigma_\phi + \sigma_b < \sigma_m$; σ_m is the allowable stress (113MPa) (6)

The thermal stress in the second wall can be neglected because of its thinness and of the absence of the surface heat flux.

Case II: Flat plate with round corners

For this case, the maximum mechanical stress induced by the coolant pressure occurs at the corner instead of the center of the canister first wall, and is estimated by the following equation:

$$\sigma_\phi = \frac{r P_2}{t} + \frac{6\,P_2\,r\,d}{t^2}\left(1 + \frac{t}{3\,r} + \frac{t^2}{10\,r^2}\right);\quad t=t_1+t_2 \qquad (7)$$

where r and d are the round corner radius and the half length of the flat plate, respectively. Since this maximum stress occurs at the end of round corner and not at the first wall center, the criteria given by eq.(5) is more sever than actual one. The factor F in eq.(2) is assumed to be 1.0 in this case since the flat part is like a straight rectangular channel.

2.2 Results

Case I: Elliptical shape canister

The modification factor, F, in eq.(2) is evaluated by comparing 3-dimensional results for a rectangular channel with a semi-circular bend to 1-dimensional results and by assuming that the F-values obtained also apply for elliptical bends. A half region of a rectangular pipe with a semi-circular bend was analyzed with the ANSYS 3-dimensional finite element code[3]. The model used eight node solid elements with a total number of 224 elements and 432 nodes. The calculated stress distribution along the longitudinal direction at the coolant side is shown in Figure 3 for a first wall thickness of 4 mm and a rib spacing of 3.4 cm. The distribution is parabolic and the absolute value of the stress at the ends is twice that at the center. This result confirms the assumption that this stress is caused by the bending moment. The values of F calculated from this analysis are 0.55, 0.44, 0.35, 0.29 for distances between ribs of 3.4 cm, 5.0 cm, 6.6 cm and 8.2 cm respectively. For rib spacings other than the above values, F was evaluated by extrapolation.

The required wall thickness of the first wall and its corresponding second wall thickness to satisfy the ASME Code criteria (eqs. 4-6) are shown in Figure 4, where the minor radius is 60 mm and the rib spacing is 40 mm. For a surface heat flux of 0.3MW/m^2, the constraint is due to the primary stress; however, for a surface heat flux greater than 0.45 MW/m^2, the thermal stress increases and limits the thickness of the first wall. As shown in Figure 4, for a heat flux of less than about 0.4MW/m^2, this results in a minimum total wall thickness of 7.7 mm (6 mm for the first wall and 1.7mm for the second wall). The available first wall breeding space is shown in Figures 5-7 for different surface heat fluxes and for ellipse minor radii between 30mm and 165mm (perfect circle). The vertical axis represents the ratio of the available space in the first wall region (excluding the structure and first wall channel) normalized to the equivalent available space of a rectangular canister with the assumption of a total wall thickness of 5mm and a first wall channel thickness of 3mm. For surface heat fluxes up to 0.3MW/m^2, the optimized minor radius of the canister is around 60mm. This seems reasonable because even though a smaller minor radius would increase space utilization, more structural material would be required to satisfy eqs.(4) and (6). 15% more first wall region space is available with the optimized shape when compared with the space available for a semi-circular first wall. With increasing surface heat flux, the optimized minor radius is the same for a coolant channel rib spacing of 3 cm. For larger rib spacing, the minor radius for space maximization is increased because of the influence of the bending moment.

Case II Flat plate with round ends

The required thicknesses of the first wall and second wall are shown in Figure 8. The results were obtained by assuming that the radius of the round corner and coolant channel rib spacing are 160mm and 20mm, respectively. To satisfy the stress criteria the minimum total wall thickness corresponds to a first wall thickness of about 7 mm and a second wall thickness of about 2 mm for a surface heat flux equal to 0.3MW/m^2. Figure 9 shows that the maximum ratio of available space is 77% for a 0.3 MW/m^2 heat flux when the shape is the semi-circular one. This result indicates that space utilization is poorer when using this type of canister first wall shape due to much more structure needed to satisfy the stress criteria.

The analysis in effect shows that there is an increase of about 15% space utilization in first wall region using an elliptical shape instead of a semi-circular one. However the total wall thickness for the ellipse(7.7mm) is higher than for the semi-circular(5mm). The final choice of the first wall shape will fall between these two shapes and will depend on the trade-off between a higher tritium breeding ratio for the minimum structure case and a potentially lower cost for the more compact blanket case.

3.LIFETIME EVALUATION

The first wall life time performance was evaluated using 2-dimensional linear elastic fracture mechanics mechanism [4,5] for the optimized design which was obtained from the previous section . The analyses were performed at two different locations, namely at the edge and the center of the canister first wall, for a surface heat flux of 0.3 MW/m^2 and a wall thickness of 6 mm. These two locations were chosen because the bending moment induced by the coolant pressure has its maximum and minimum values at these points. The calculated crack growth behavior at the edge of the coolant channel is shown in Figure 10 for different initial crack lengths. For this example, the assumed initial crack shape is a half ellipse normal to the ribs. The result indicates that the crack at the coolant side propagates first but stopped growing because of the change of the stress distribution due to creep. However, the crack at the plasma side propagates rapidly after about four months of operation. For two years of operation, the maximum allowable initial crack length should be less than 1.5 mm. Similar crack growth behavior can be found at the center of the coolant channel. Calculations were also done for cracks parallel to the ribs and they were found to grow much slower. The cracks at any location for these cases propagate less than 2 mm after 2 years of operation assuming a 1mm initial crack length and a surface heat flux of $0.3MW/m^2$.

4.CONCLUSION

The choice of the canister first wall shape depends on the relative importance of maximization of space utilization for greater compactness and minimization of structure for higher tritium breeding. For space maximization the optimized canister first wall shape is an ellipse with a 60 mm minor radius and a 165 mm major radius. For structure minimization, the optimized first wall design is a semi-circular shape. The results also show that for higher surface heat fluxes, smaller rib spacings are required. Life time analysis shows that the crack normal to the ribs is critical and that a maximum of 1mm initial crack length could be tolerated for 2 year of operation. An interesting follow-up to this work would consist of a 3-dimensional analysis for the whole canister considering the side walls and the surface of the first and side walls, and of a detailed analysis of the cost and tritium breeding trade-off.

ACKNOWLEDGMENTS

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Table 1 List of majior parameter for helium-cooled solid breeder

Canister		Coolant	Helium
Length (m)	1.2	Inlet/outlet temperature (°C)	50/300
Height (m)	0.33	Inlet/outlet pressure(MPa)	1.5/1.4
Depth (m)	0.7	Neutron wall loading	
Number	48	Average/maximum (MW/m^2)	1.5/1.9
		Maximum nuclear heating rate (W/cm^3)	9

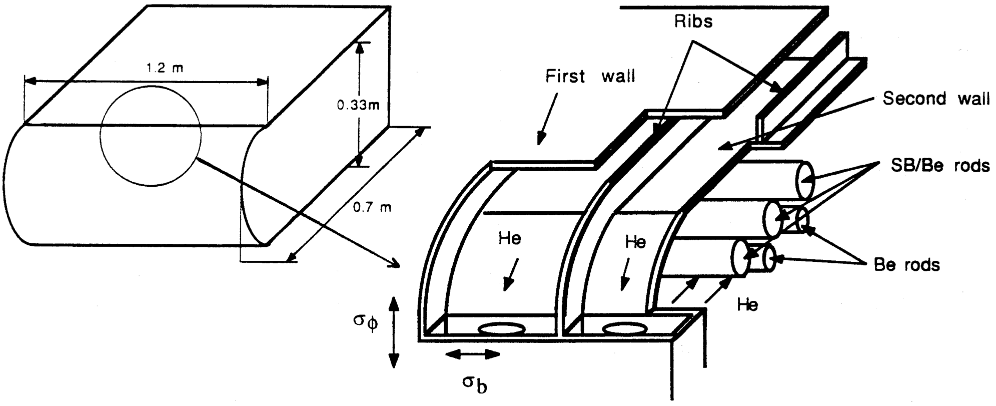
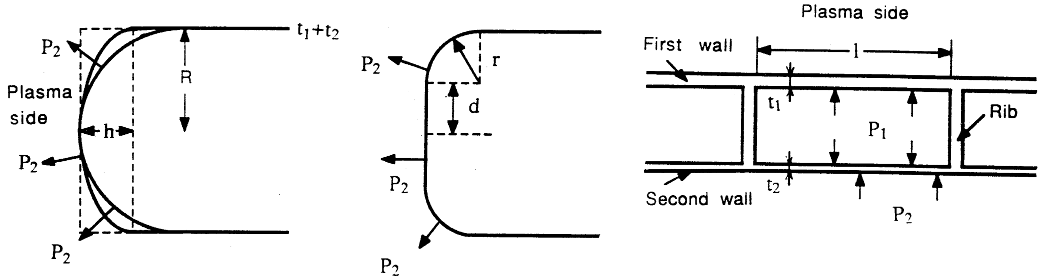


Fig.1 Schematic view of canister and its head



(case 1) (case 2) (case 1 and 2)

Fig.2 Model to evaluate mechanical stress

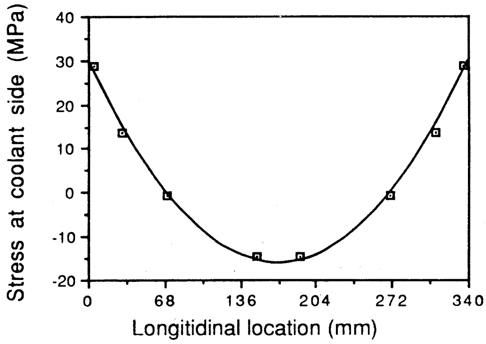


Fig.3 Stress distribution along longitudinal location

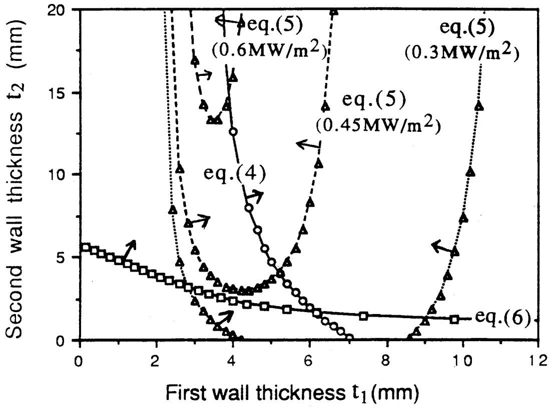


Fig.4 Relation between first and second walls (case 1, h = 60mm l = 7cm)

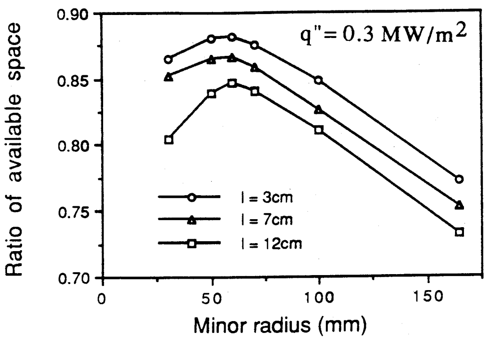


Fig.5 Ratio of available space (case 1, q"=0.3MW/m^2)

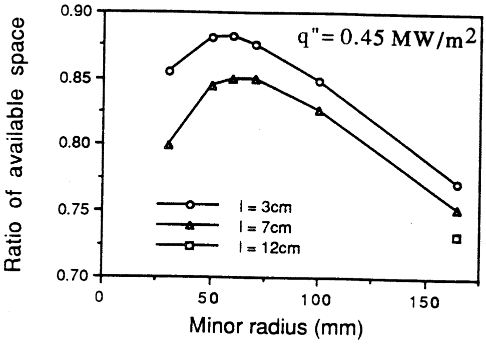


Fig.6 Ratio of available space (case 1, q"=0.45MW/m^2)

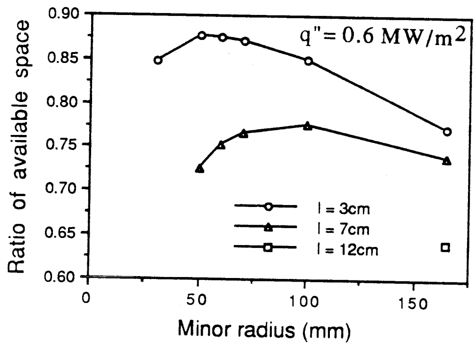


Fig.7 Ratio of available space (case 1, q"=0.6MW/m^2)

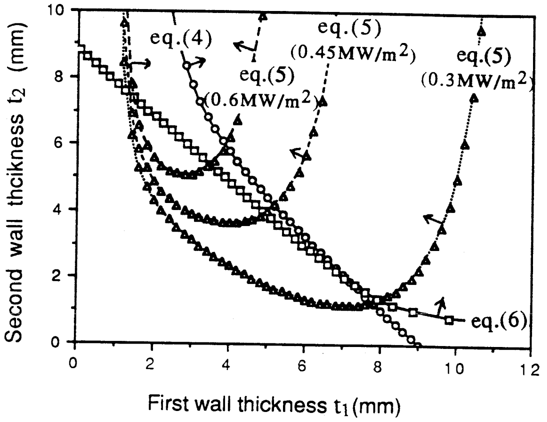


Fig.8 Relation between first and second walls (case 2, r =160mm, l =3cm)

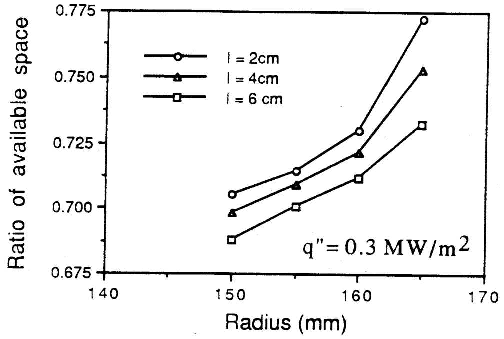


Fig.9 Ratio of available space (case 2, q"=0.3MW/m^2)

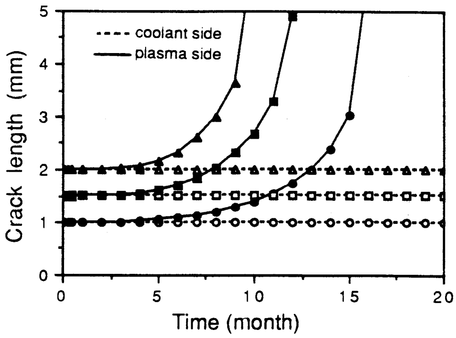


Fig.10 Crack growth