

TRITIUM-PRODUCING BLANKET FOR FUSION ENGINEERING FACILITY *

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The usefulness of ITER to fusion development can be substantially increased if the design parameters and features are selected so as to maximize reactor relevance without significantly increasing the risk. One critical area in which reactor relevance and risk are major issues is the tritium-producing blanket. A helium-cooled solid breeder blanket is found to offer the highest potential for a low-risk reactor-relevant blanket that can meet all the ITER requirements. It has many attractive features that include: (1) a large design margin to account for uncertainties in predicting the effects of the fusion environment; (2) an available data base that is rapidly expanding worldwide; (3) flexibility in accommodating changes in the operating parameters of ITER (e.g. fusion power and wall load); (4) solid breeder operation at reactor relevant temperatures and flexibility in setting the helium temperature to reduce risk and/or optimize the structure temperature while keeping the helium pressure at a modest level; and (5) safety features, including the use of inert gas with no chemical reaction or corrosion, a low activation solid breeder, and multiple containment of tritium.

1. Introduction

A helium-cooled solid breeder blanket has been proposed for ITER with the idea of developing a low-risk blanket option with reactor relevant materials and configuration. Some of the more attractive features associated with this proposed blanket option are:

(1) There is a significant design margin since the wall loading ($1-2 \text{ MW/m}^2$) and fluence ($3 \text{ MW}\cdot\text{yr/m}^2$) of ITER are substantially lower than the wall loading (up to 5 MW/m^2) and fluence (up to $20 \text{ MW}\cdot\text{yr/m}^2$) of commercial reactor designs and only part of the allowable solid breeder temperature window needs to be used.

(2) There is an expanding data base available from the number of past and on-going solid breeder experiments carried out internationally. It is expected that data will be available from these experiments in fission reactors for the fluence expected in ITER.

(3) The solid breeder can be designed to operate at high temperature, providing valuable information applicable to reactor conditions, while the helium is kept at a moderate temperature and pressure for safety and reliability.

(4) Since helium is a gas, the pressure increase for any temperature increase is minor compared with a

saturated liquid. Thus, the helium flow rate and/or inlet temperature can be adjusted without incurring any substantial pressure penalty. The helium temperature can then be set so as to optimize the structure temperature and to accommodate any long-term power variation.

(5) Safety is expected to be a key factor for ITER. In this respect, the use of helium, an inert gas precluding any chemical reaction and corrosion, in combination with a low activation solid breeder, such as Li_4SiO_4 and Li_2O , is highly appealing.

Some of the key technical areas addressed in this work for the helium-cooled solid breeder design include the achievable TBR, the coolant pressure requirement, the provision for producing the required temperature drop between the high-temperature breeder and the lower-temperature coolant, and the helium containment and manifolding. The results of the design and analysis efforts indicate that all absolute requirements can be met in a low-risk, reactor-relevant blanket with many attractive features.

2. Concept design

The design is based on previous studies [1,2] and consists of a number of independent canisters, lying side by side in the poloidal direction, as shown in fig. 1

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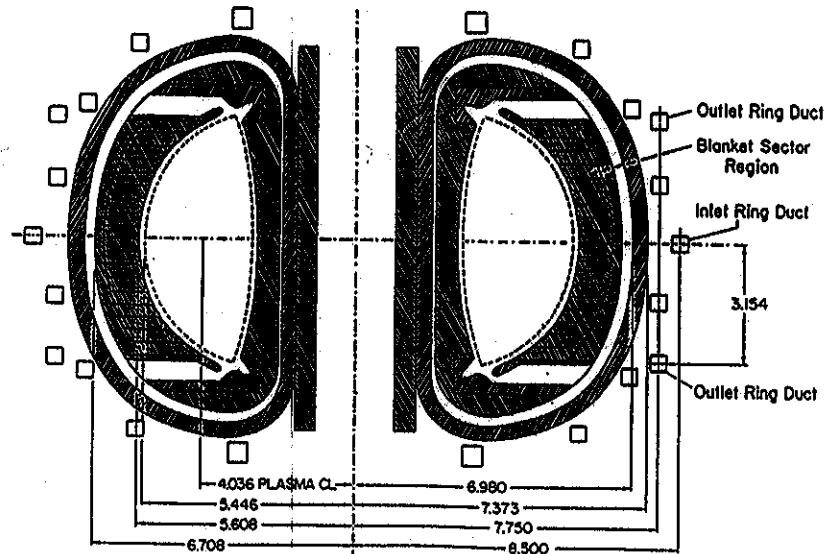


Fig. 1. Cross-section of ITER canister layout.

for the outboard of the reference ITER design. A rod bundle configuration inside each canister is chosen for the design calculations. In this configuration, the solid breeder and multiplier are in well-defined volumes to enhance the predictability of their properties. They can also be placed in the same rods or in different adjacent rods, creating a near-homogeneous mixture which increases the neutronics performance. In addition, such a configuration provides the flexibility of varying individual rod sizes and compositions in different rows to allow for the exponential decrease in heat generation in the radial direction while maintaining the solid breeder at an acceptable temperature. Finally, a rod bundle configuration provides reasonable heat transfer and pressure drop and has been well studied in heat exchanger designs. Note that the rods are staggered to reduce radiation streaming in the main blanket region. However, the effects of radiation streaming in the plenum and manifolding must be accounted for in the design of the shield and manifolds.

Figure 2 shows a typical canister with the solid breeder and/or multiplier rods. In the design, the canister width is 33 cm and its length is 1.1 m. The reason for using these small canisters is to maximize the coverage of available space on the outboard of the ITER reactor, where space allowances are required for test modules and penetrations. A single main helium flow is shown in this design to reduce the manifolding complexity. The flow comes in along the side wall to pro-

vide for the cooling of the first wall and then enters the canister at the first wall and flows over the rod bundle before exiting the canister at the back. A porous mesh is provided along the side wall helium channel so that a stagnant layer of helium inside the mesh will act as an insulator between the cooler side wall flow and the hotter rod-bundle flow.

For simplicity, a single rod configuration is shown inside the canister. However, the canister could easily be divided into two or three regions with different rod configurations in each, as required by neutronics or other consideration. The smaller rods are beryllium rods which are clad to preserve the integrity of the beryllium and to provide a barrier against contamination of the main helium flow from tritium produced in the beryllium. The larger rods consist of a clad solid breeder inner cylinder with a clad sphere-pac Be/He annular region on the outside.

The use of beryllium particles and helium in the thermal resistance gap between the solid breeder and helium is proposed because it offers several advantages, including the following:

(1) The thermal resistance between the solid breeder material and coolant can be selected by properly tailoring the bed characteristics (porosity, type and size of particles, type of gas).

(2) The increased gap size, as compared with pure helium, allows for better uniformity and predictability of the thermal resistance.

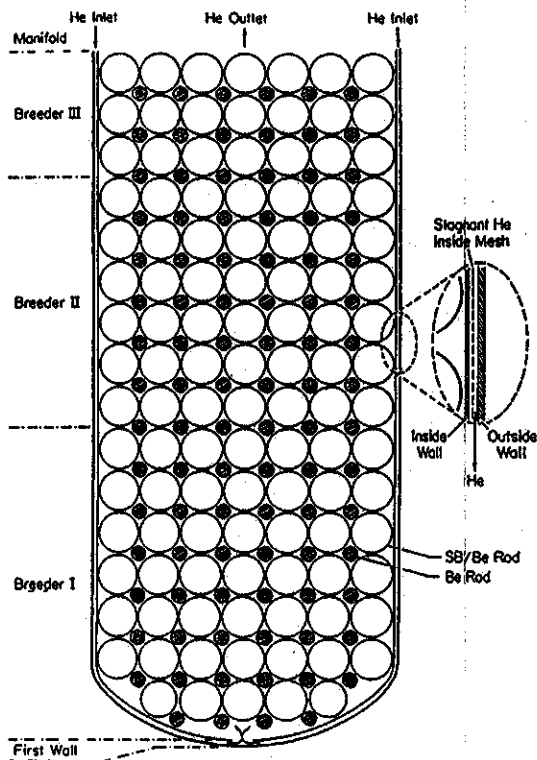


Fig. 2. Helium-cooled solid breeder blanket canister for ITER.

(3) The use of beryllium in a near-homogeneous mixture enhances the tritium breeding capabilities of the design.

(4) Increased control over the solid breeder temperature (through both passive and active means) permits operation over a wider range of power densities and transient conditions without violating temperature constraints.

(5) Swelling can be partially accommodated by expansion into the bed void fraction.

(6) Tritium generated in the beryllium multiplier is more easily removed, perhaps as a part of the basic solid breeder purge system.

(7) An additional purged barrier is provided against tritium permeation to the coolant.

2.1. Neutronics

A series of 1D calculations using toroidal and poloidal geometry models were first performed to discuss the impact of design options on tritium breeding. A 3D calculation using a Monte Carlo code was per-

formed for the final design to provide a more accurate evaluation of the net TBR.

The materials considered for the neutronics calculations are Li_4SiO_4 (based on the discussion in ref. 3), beryllium, and PCA as breeder, multiplier, and structure respectively. For these initial calculations the TIBER [4] water-cooled inboard shield configuration was adopted, with a total thickness of 55 cm. The design and optimization of a helium-cooled inboard shield should be done later as a trade-off between the attractive safety feature of heaving an inert gas and the expected cost penalty of requiring more shielding material to account for the helium voids. For the present, since the inboard shield will require a separate cooling circuit for any blanket, it is reasonable to assume that the inboard shield, away from the lithium-carrying test modules in the outboard, can be water-cooled.

It is not clear exactly how to derive a net TBR from the 1D value of 1.35 obtained using the toroidal arrangement. The problem is difficult because of the uncertainties introduced by loss of coverage due to test modules and penetrations, and also by the fact that breeding can be done in the top and bottom parts of the inboard and in the divertor regions, particularly if a single null poloidal divertor design is assumed. As a result, the 3D MCNP neutronics code was run assuming homogeneous regions for the case which maximizes the coverage, with breeding on the outboard, top flat region (assuming a single null divertor design), top corner and lower inner corner, but excluding the space-limited 4 m high inboard shield. Based on the 1D calculation optimization, a 90% ^6Li enrichment is assumed along with a 85/15% mix of beryllium and solid breeder in the breeder regions. The configuration for the 3D calculation is shown in fig. 3. Notice that there is much more space in the top corner than in the inboard region and there is no difficulty in providing adequate shielding. Ease or difficulty of maintenance will depend on the actual configuration and maintenance scheme selected for ITER. For example, the commonly used scheme of removing the sector in order to replace a module will make the outboard and top corners comparable from a maintenance standpoint. There is also adequate space in the top and bottom region that can be used for manifold.

The TBR results are summarized in table 1. They are quite conservative since the neutronics calculations assume a uniform source and no plasma MHD shift, both of which would increase the outboard contribution to the TBR. The results are encouraging and show flexibility as a number of different regions can be included

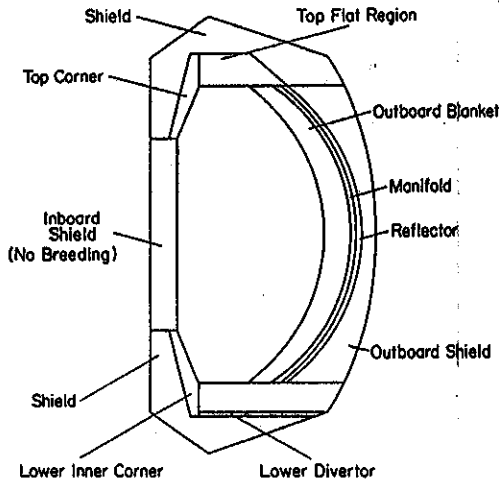


Fig. 3. Configuration for 3D neutronics calculations.

depending on the TBR requirements. A TBR of ~ 1.27 can be obtained without breeding in the space-limited inboard region. Void space for penetrations is a modest penalty since there is no substantial loss of neutrons, and space required for test modules might also not be a penalty if even partial breeding from the modules is taken into account. However, even if an assumption is made that out of the 217 m² of the outboard, 29 m² is not available for breeding and that another 3% coverage is lost due to plenum and structural requirements at the canister end walls, an overall net breeding ratio in excess of unity is obtainable. The margin in excess of unity can be used to simplify the design, for example, by eliminating breeding in the access-limited lower corner region.

The above analysis and discussion indicates that even by being conservative with this initial configuration, we can design for at least a 3D net TBR of unity

Table 1

TBR results from 3D neutronics calculations for ITER helium-cooled solid breeder blanket

Region contribution to TBR:	TBR
Outboard blanket	1.01
Top flat region	0.082
Top corner	0.064
Inboard shield (no breeding)	0.0
Lower inner corner	0.067
Lower divertor	0.06
Total TBR	1.27

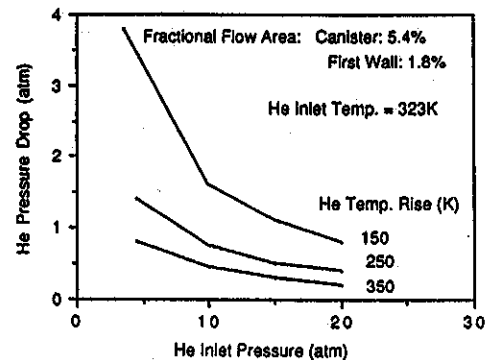


Fig. 4. Canister helium pressure drop as a function of the inlet pressure for different temperature rises.

even when including space loss penalties and without breeding in the space-limited inboard region. The flexibility of the configuration allows a trade-off between increasing the number of breeding regions to meet higher TBR requirements and increasing the manifolding and maintenance complexity for less accessible regions.

2.2. Thermal-hydraulics

Figure 4 shows the canister helium pressure drop, ΔP , as a function of the inlet pressure, $P(\text{in})$, for different helium temperature rises, ΔT_{He} for the case with 4 cm rods and 2 mm spacings. Even if the pressure drop is doubled or tripled to account for the helium flow outside the canister (as our calculations indicate), a wide range of $P(\text{in})$ and ΔT_{He} choices is available. The corresponding pumping power requirements is less than 20 MW for all cases with $P(\text{in}) \geq 10$ atm and $\Delta T_{\text{He}} \geq 250$ K.

A $P(\text{in})$ of 1.5 MPa and a ΔT_{He} of 250 K are reasonable design choices; the required pumping power for the complete helium circuit, including the piping and heat exchanger, is about 22 MW. The low stress caused by the pressure will facilitate the design of canister structural configuration.

2.3. Power variation allowance

This blanket is very flexible in allowing for operation at 50% below or above the design power level. Both passive and active ways can be employed to allow for power variation. The passive way makes use of the large solid breeder temperature window, whereas the active way makes use of the helium temperature which can be varied by changing the inlet temperature and/or flow

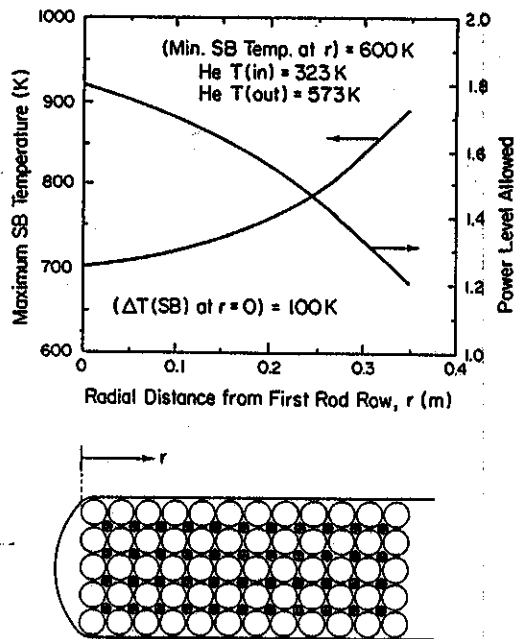


Fig. 5. Maximum solid breeder temperature and power level allowed.

rate without any significant pressure penalty. Conservatively, the added flexibility of adjusting the purge to control the Be/He particle bed thermal conductivity is not considered here.

Figure 5 illustrates the flexibility of the design in this regard for a canister located at the highest wall loading location (1.9 MW/m^2). The figure shows the maximum solid breeder temperature in the first row as a function of the thickness, r , of a uniform first breeder region. The minimum temperature of the solid breeder at r is 600 K. Any increase in the power level is allowed by letting the solid breeder temperature in the first row rise to the maximum allowable temperature, 1000 K. Thus, for a 20 cm thick first breeder region, as an example, the maximum solid breeder temperature in the first row is 760 K and the allowable increase in power is 50%. There is a trade-off here between the allowable power variation and the number of uniform regions per canister and the number of canister configurations also, since the wall loading varies poloidally. Our calculations indicate that, to allow for a 50% increase in power, two or three different canister regions and three and four different canister configurations are required. Note that, any decrease in power can be easily accommodated with no apparent penalty by increasing the helium temperature through a reduction of its flow rate and/or an increase in its inlet temperature.

2.4. Reliability

The reliability of the blanket is often thought to decrease as the number of rods increases. The overall consequence of failure, though, does not necessarily follow the same trend since the reduced consequences of failure per rod can outweigh the increased probability of rod failure in designs with a larger number of smaller rods. To address this issue, the probability of achieving a given level of consequences was investigated in different designs. The calculations performed assume that tritium contamination is one of the most serious consequences of rod failure. It was found that for each set of assumptions used (e.g. the probability of one rod failure), there is a critical value for the amount of tritium release over which the consequence of rod failure decrease as the number of rods increases.

In summary, the rod design is very robust against failures. It provides multiple barriers against contamination. With the inert coolant, the consequences of failure are not catastrophic, at worst leading to contamination of the main coolant. The rod design also dilutes the source term, and increasing the number of rods can actually decrease the probability of exceeding contamination limits.

2.5. LOCA

Figures 6 and 7 summarize the results from the initial LOCA calculations. They illustrate the change in time of the temperatures of the first wall and the Li_4SiO_4 solid breeder in the first row of rods following a LOCA. Under adiabatic conditions, in time both the

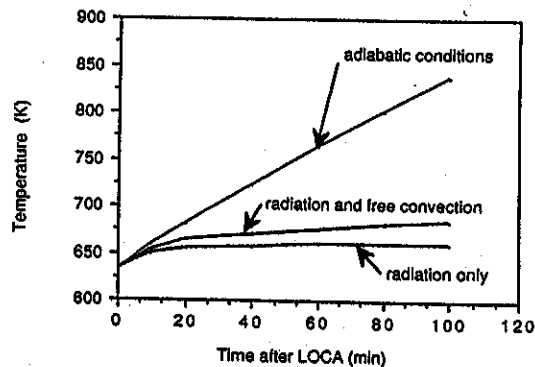


Fig. 6. First wall temperature following a LOCA for three cases: (1) adiabatic conditions; (2) inclusion of radiation cooling to inboard; (3) inclusion of radiation cooling and heat transfer by free convection between solid breeder and first wall.

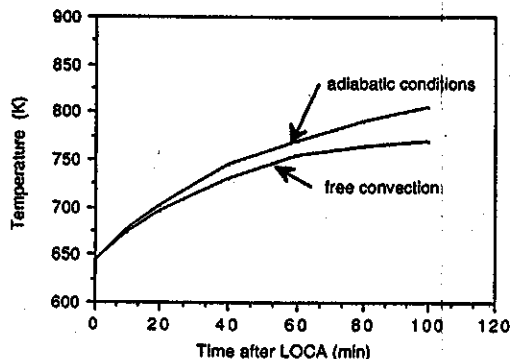


Fig. 7. Solid breeder temperature following a LOCA for two cases: (1) adiabatic conditions; (2) inclusion of heat transfer by free convection between solid breeder and first wall.

first wall structure and solid breeder would exceed their maximum allowable temperatures resulting in loss of investment. If radiation to the cooled inboard is assumed the first wall temperature stays under half its melting point of about 1700 K. Including the effect of free convection (which results in heat transfer from the hot solid breeder to the colder first wall) slightly increases the first wall temperature but only retards the time for the solid breeder to reach its maximum allowable temperature of 1000 K (based on sintering).

A possible solution would be to connect a helium cover gas in the building to a heat exchanger to create a draft which could be enough to increase convection and keep the solid breeder rods and first wall acceptable temperature levels, with no loss of investment. However, key issues must be addressed, such as whether it is feasible or desired to keep the cover gas at 1.5 MPa or whether the cover gas could be pressurized only when a LOCA occurs. Further analysis is required in this area.

2.6. Helium leakage to plasma

It is very difficult to predict the helium leakage to the plasma accurately, but some observations can be made. Extrapolation of the data from Fort St. Vrain HTGR [5] indicate that the leakage rate through welds to the plasma is only about 1% of the helium generation rate in the plasma based on an estimated 4700 m total weld length exposed to plasma. However, estimates assuming cracks through the whole thickness of the first wall, could increase the above number substantially. The difficulty of accurate calculations is increased by the fact that the number and size of cracks escaping inspection are not known and that mechanisms such as crack growth must be considered. Including this consid-

eration in the design process can help alleviate the problem. For example, crack propagation is more problematic in welds, and the number of welds in contact with the plasma can be minimized. Note also that any reasonable amount of helium leaking to the scrape-off region would be swept away in the divertor and would probably provide a beneficial effect by cooling the plasma edge. Further effort is required in this area to find out the extent of the problem, and, if required, to develop acceptable solutions.

2.7. Tritium Inventory

The steady-state tritium inventory in the Li_4SiO_4 breeder is estimated to be very low, 1.5 g. Radiation effects can increase this inventory. However, even if a factor of 100 increase results from radiation effect, the tritium inventory would still be significantly smaller than in other candidate concepts. The concern regarding tritium accumulation in beryllium is lessened in this design since the beryllium is also purged. However, the effect of a BeO layer and of its thickness on the tritium inventory inside the beryllium spheres should be considered as it could freeze much of the tritium inside the beryllium.

3. Summary

The helium-cooled Li_4SiO_4 blanket concept for ITER is attractive from several points of view, such as the well-studied configuration, the expanding data base, the safety, and the information it provides on reactor-relevant solid breeder operation at reactor temperatures. The key issues of neutronics, thermal-hydraulics, and gap conductance have been addressed. A net TBR in excess of unity can be designed for with breeding margin for uncertainties. The helium pressure and inlet and outlet temperatures are moderate (15 atm, 323 K and 373 K) and do not pose any significant penalty on the structural design. Helium cooling provides flexibility in selecting the optimum temperature for structure and in allowing for power variation. A novel and practical concept has been proposed for the thermal resistance gap between the solid breeder and the coolant. The concept is applicable to other blanket concepts and should be verified experimentally.

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