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ABSTRACT

The nuclear performance of a candidate fission-suppressed, U233-producing blanket is assessed. It is predicted to have a breeding ratio (fusile + fissile) of 1.68 and produce U233 at a rate of 8030 kg/year from 3140 MW of DT fusion and a blanket coverage of 96%. Blanket energy multiplication is estimated to vary between 1.3 and 2.0 as the U233/Th232 ratio varies between 0 and 0.5%. Heterogeneous effects in the blanket's pebble-bed configuration were found to be important and more detailed analysis is needed to more accurately predict Li6 content required and U233 fission power versus U233 content.

INTRODUCTION

The conceptual design and analysis of fissile-producing blankets for fusion breeders is the primary activity of the fusion breeder project. Our recent (FY82) efforts have been directed toward developing a fission-suppressed blanket design evolving from earlier work[1-3] and based where possible on conventional materials and processes. The result is a blanket composed of Be pebbles ($\sim$ 50 v/o) for neutron multiplication, Li ($\sim$ 40 v/o) for T breeding and cooling, and steel for structure. Each Be pebble has a Th ($\sim$ 3 v/o) snap ring or insert for U233 breeding. The Li-cooled pebble bed design allows for removal, reprocessing and refueling without blanket disassembly. A rendering of this blanket designed for a tandem mirror-DT fusion neutron source is shown in Fig. 1.

This paper deals with the nuclear design and analysis of this conceptual blanket. Mechanical and other aspects of this blanket design are treated in companion papers.[4-7]

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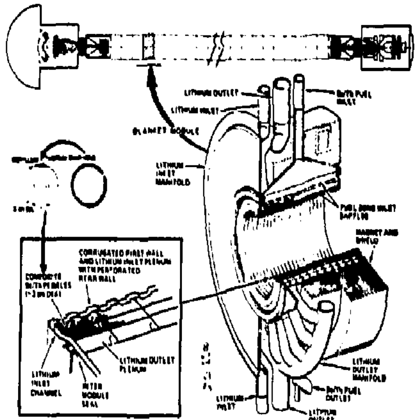

Fig. 1 Reference blanket for the Tandem Mirror Fusion Breeder

OBJECTIVES AND METHODS

Tritium and U233 breeding, energy multiplication, criticality and power density versus fissile buildup are nuclear parameters important in the design and evaluation of blankets for fusion breeders. The basic nuclear objective of a fission-suppressed blanket is to maximize fissile breeding while breaking even in tritium ($T \sim 1.0$), suppressing fission of both the fertile and bred fissile materials, and remaining subcritical under all conditions. In addition to the nuclear objectives, blanket structure, heat transfer, and fuel handling requirements must be met. Thus, an interactive and iterative design process is used.

If nuclear performance was the only requirement, the blanket would be a homogeneous mixture of beryllium (Be) plus a few atom percent Li6 and Th, and its tritium plus fissile breeding ratio (T + F) would be about 2.7.[1] Thus, the potential nuclear performance of the Be blanket is high. The question addressed here is how much of this potential performance can be achieved when structure, heat transfer, and other blanket engineering requirements are met.

Method

The method used for nuclear analysis of the blanket is TARTNP, a coupled neutron-photon, 3-D Monte Carlo transport code, and 175 group constants generated from ENDL, the Livermore-evaluated nuclear data library.[8,9]

Four types of geometric models were developed to predict the blanket's nuclear performance. The first is a radial-zoned cylinder, the second a radial- and axial-zoned cylinder, the third a radial-zoned spherical unit cell, and the fourth a cylindrical segment containing unit fuel cells imbedded within homogenized fuel zones. These models evolved during the course of the study as the mechanical design and understanding of the nucleonics evolved.

The first model is the basic model used to predict the integral performance of the blanket. The additional models were developed to examine effects the basic model did not address. Results generated using these additional models were used to modify results from the basic model to arrive at a more accurate estimate of performance.

Cylindrical (1-D) Model

The basic model used to analyze the blanket is a nested set of concentric cylindrical shells surrounding a cylindrical source of 14-MeV neutrons. The geometry and composition of the blanket for the base case are shown in Fig. 2. Starting at the left in the figure is the first wall, consisting of 2 Fe zones separated by a 5.3-cm coolant plenum containing Li + 2.5 v/o Fe. The 2.5 v/o Fe accounts for stiffening ribs. Following the first wall are two 20-cm-thick packed beds composed of Be/Th spheres, Li coolant and Fe structure. Each bed consists of Li (40 v/o), Be (57 v/o), thorium (3 v/o) plus 2 v/o Fe superimposed to account for the radial stiffeners. The Be and Th are 98% of theoretical density. The two beds are separated by a 1-cm Fe wall and are followed by 1.3 cm of Fe, 30 cm of Li + 2.5 v/o Fe, 2 cm Fe and finally 10 cm of graphite. The outer graphite surface is a radial leakage boundary while the ends (axial) are reflecting boundaries. Making the ends reflecting boundaries is considered reasonable because in the reactor the plasma extends beyond the blanket; therefore, the net axial leakage should be insignificant. Each of the two packed beds are divided into two 10-cm zones to get better resolution of the spatial reaction rates and heating in the beds.

The Li6/Li ratio in the homogenized model of the beds (1%) is higher than in the Li-only zones (0.2 %) to account for the heterogeneous effect of the bed geometry. This point is discussed further, later in the paper. The optimum Li6 concentration is yet to be determined. The different Li6 concentrations used in the model are an artifact of the model; the blanket really has only one Li6 concentration.

Performance parameters calculated with this base model are given in Table 1 which lists reactions and resulting breeding ratios at three enrichments (% U233 in Th) 0, 0.25 and 1.0. Net breeding is 1.83, and energy multiplication (M) is 1.39, 1.66, and 2.14 for these three cases. Statistical accuracy is within about 5%. The U233 fission as well as U233 n,gamma reactions were found to be directly proportional to U233 concentration, at least up to 1.0 a/o. It is also interesting to point out that the capture reactions of benefit, in Li6 and Th232, account for 87% of the total captures. The Fe structure accounts for 6% of the captures. When compared with an ideal blanket value of 2.7, this blanket model achieves 70% of ideal breeding. The difference is the result of moderation by materials other than Be and a relatively thin blanket, thus reducing Be (n,2n) reactions and allowing more leakage. At a 1 MW/m^2 source neutron wall loading and a 1% U233 concentration in Th, the maximum volumetric heating in the first wall is 7.3 w/cc and the maximum and minimum heating in the homogenized packed beds (zones 7 and 11) are 6.9 and 1.3 w/cc.

Axial Heterogeneous Model

The basic cylindrical model does not account for the lithium inlet and slipstream plena at the ends of each module. To estimate their effect, a 21-cm-long axial section at the end of the 4-m blanket module is replaced by a zone containing 90 v/o Li (0.2 a/o Li6) and 10 v/o Fe. By symmetry the model used is 1/2 the module length and is shown schematically in Fig. 3. The effect is a 2.9% drop in net breeding and a 2% drop in M.

A similar model was also used to examine the effect of homogenizing the radial stiffeners. This was done by removing the 2% Fe from the beds and the lithium plena and putting it into a 0.61-cm axial zone on the end of a 30.5-cm blanket segment. There was no detectable effect. Therefore, no correction is used to account for homogenizing the radial stiffeners.

Spherical Unit Cell Heterogeneous Model

The basic cylindrical blanket model

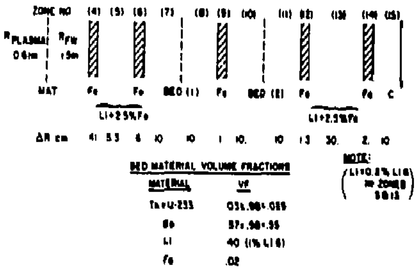

Fig. 2 Cylindrical model - geometry and composition

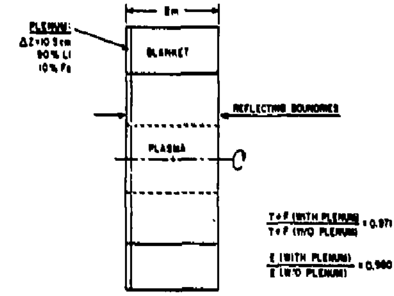

Fig. 3 Module end plena - model and results

Table 1 Cylindrical model - results per D-T Neutron at 0/0.25/1.- a/o U233

Zone #	Li6 (n,T)	Li7(n,n'T)	Th232(n,γ)	Th232(n,fiss)	U233(n,fiss)	U233(n,γ)
5	.055/.059/.056	.130				
7	.283/.303/.287	.061	.298/.315/.310	.0036	0/.0054/.0209	0/.00084/.00327
8	.252/.253/.248	.029	.225/.234/.237	.0018	0/.0043/.0170	0/.00068/.00268
10	.144/.154/.147	.011	.125/.132/.133	.0007	0/.0025/.0101	0/.00040/.00161
11	.081/.089/.090	.005	.068/.073/.079	.0003	0/.0014/.0060	0/.00023/.00096
13	.049/.039/.055	.011				
Totals	.814/.897/.883	.247	.716/.754/.759	.0064	0/.0136/.0540	0/.00215/.0085

Bottom Line:

T = 1.12/1.14/1.13, T + F = 1.83/1.90/1.89,

$T + F_{net}{}^{*}$ = 1.83/1.88/1.83

M = 1.39/1.66/2.4

* F_{net} = Th232(n,γ) - U233(n,fiss) - U233(n,γ)

** Includes equilibrium decay of actinides and fission products in the beds

***Totals include structural zones.

Zone #	Energy (MeV) per Source 14.1 MeV Neutron**
5	2.35/2.28/2.35
7	6.78/8.31/10.77
8	4.44/5.45/7.72
10	2.24/2.84/4.26
11	1.23/1.51/2.47
13	0.58/0.41/0.65
Totals***	19.5/23.3/30.1

treats the packed beds as homogeneous mixtures of Li, Be, Th/U and Fe. To determine if there are heterogeneous effects in the beds, two models were developed. Breeding ratio, energy multiplication, energy partitioning in the bed materials, and isotopic composition of the Li required to give the correct tritium breeding ratio are all nuclear performance parameters that could be affected by heterogeneous effects.

The first model developed to appraise these heterogeneous effects is a spherical unit cell consisting of a Th (+ U) sphere surrounded by a Be annulus which in turn is surrounded by a Li annulus as shown in Fig. 4. Volume fractions of these materials in the unit cell are Th (3%), Be (57%), and Li (40%). The Be contains 0.1 a/o Fe impurity. An isotopic point source of 14 MeV neutrons is located in the outer Li zone. The outer surface of the cell is a reflecting boundary making the cell an infinite array of unit cells.

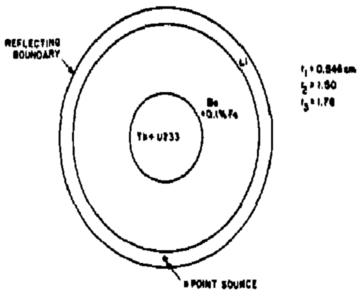

Fig. 4 Spherical unit cell model

By comparing the nuclear parameters calculated with this unit cell to those calculated with a homogenized version of the same cell, an estimate of the heterogeneous effect can be made. Results for two U233 concentrations, 0 and 0.25 a/o in the Th, are given in Table 2. The factor of 5 difference in Li6/Li7 ratio between the heterogeneous (0.2%) and homogeneous (1.0%) cases is needed to keep the tritium breeding ratio (T) approximately equal. These results indicate that heterogeneous effects in the pebble beds are significant. For these cases the net breeding ratio ($T + F_{net}$) dropped between 5.5 and 7.7% and the change in M ranged between 5% lower to [illegible] higher than their homogeneous counterparts. An increase in M is expected for the same reasons a thermal reactor with a heterogeneous core has a higher reactivity than its homogeneous counterpart. Energy (heating) partitioning is also significant with 20 to 65% of the cell's energy being deposited in the [illegible]. This model is pessimistic in that it must overpredict U233 fission due to its infinite geometry and lack of structure. Results with this model give us an upper limit of the bed heterogeneous effects.

A number of other variations were also examined with this model. For example, with the Li6 concentrations fixed at 0.2% (het.)/ 1.0% (hom.) and the U233 concentration fixed at 0.25%, the following observations are made.

1. Changing the Th/U sphere to a 3-cm-long cylinder with the same volume reduced the drop

Table 2 Spherical unit cell sample results

	T	F	$T + F_{net}$	M	E_{Th}	E_{Be}	E_{Li}
With 0 a/o ^{233}U							
Het.	1.53	0.77	2.30	1.48	20%	33%	47%
Hom.	1.38	1.05	2.43	1.56			
Het/Homo.			0.945	0.949			
With 0.25 a/o ^{233}U							
Het.	1.54	0.81	2.27	2.47	50%	21%	29%
Hom.	1.47	1.08	2.46	1.86			
Het/Homo.			0.923	1.33			
With Th + 0.25 a/o ^{233}U moved to outside of Be pebble							
Het.	1.28	1.11	2.32	2.32	47%	26%	27%
Hom.	1.41	1.08	2.48	1.86			
Het/Homo			0.943	1.26			

With 0.2 a/o ^{6}Li (Heterogeneous) and 1.0 a/o ^{6}Li (Homogeneous)

in the net breeding ratio, from 7.7% to 5%, while further increasing M from 33% to between 34 and 64% depending on the source-slug orientation.

2. Doubling the Th/U sphere volume reduced the drop in breeding ratio to 5% while further increasing M to 44%.

3. Moving the Th/U to the outside of the Be sphere reduced the reduction in breeding to 5.7% (from 7.7%) and reduced the increase in M to 26% (from 33%). Energy partitioning in this case is 26% Be, 47% Th/U and 27% Li. This geometry was selected for the reference case to reduce thermal gradients in the Be pebbles.

Criticality

The spherical unit cell model was also used to calculate the U233 concentration (U233/Th ratio) which results in K_∞ = 1.0. Since we want k to be less than 1.0 under all potential conditions, k_∞ with and without Li vs U233 concentration was calculated. As expected, the case without Li was found to be the most restrictive with $k_\infty \simeq 1.0$ occurring at a U233 concentration of 1.6 a/o compared to 9 a/o with Li. Based on this analysis it is required that the maximum concentration of U233 + Pa233 in Th be limited to less than 1.6 a/o.

Finite Heterogeneous/Homogeneous Model

The spherical unit cell model used to estimate heterogeneous effects is an infinite-integral model, and as such cannot show spatial effects on energy partitioning. To see if spatial effects are important, a fourth model was developed. This model (shown in Fig. 5), called the Finite Heterogeneous/Homogeneous Model, is a pie-shaped segment of the blanket with reflecting sides and homogenized pebble beds, plus unit cells at the inner and outer radii of the two bed zones. The source is an

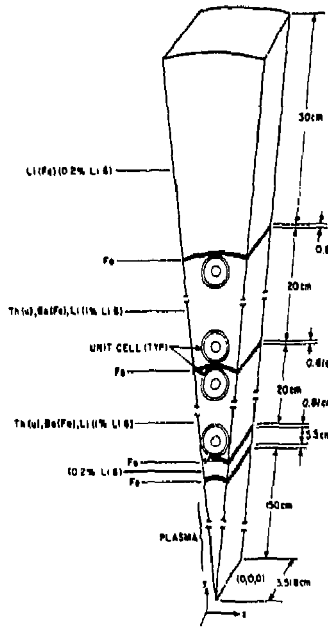

Fig. 5 Finite heterogeneous/homogeneous model

isotropic point source located at the center of the first wall. At an estimated end-of-cycle U233 concentration profile, the U233/Th ratios are 0.86% in the inner bed and 0.75% in the outer bed and in the 4 unit cells (from innermost outward) are 1.1, .62, 1.1, and .38%. Results show that energy partitioning is a function of position as well as U233 concentration. The maximum fractional heating in the Th + U is 67%, occurring at the inner radius of the outer bed, fractional heating being the ratio of heat deposition in one part of the unit cell to the total cell heating. At the highest power density location, the inner radius of the inner bed, the Th + U fractional heating is 55 percent, resulting in a power density of 141 W/cc in the Th + U at 1 MW/m^2 wall loading (not including decay heat which is about a 5% addition). The average power density in that innermost cell is 7.71 W/cc.

End Plug Effects

Fusion reactions take place in end plugs (and transition regions) that are not covered by a blanket. Not only are fusion neutrons lost, but tritium consumed must be made up by the blanket as well. Analysis has not been done to see what happens at the blanket ends. The assumption made is that the net leakage at these ends is zero. This assumption is based on the fact that the plasma extends beyond the ends, thus leakage into the blanket will occur. For this case, total fusion power is 3140 MW, 3000 of which occurs "under" the blanket. Therefore this 3140-MW fusion reactor requires a blanket tritium breeding ratio that is 3140/3000 = 1.047 times higher than the reactor requires to satisfy the tritium requirements of both the central cell and the end plugs.

ESTIMATE OF EFFECTIVE BREEDING RATIO, NET U233 PRODUCTION RATE AND BLANKET ENERGY MULTIPLICATION

Using the results calculated with the models described, the following nuclear performance estimates are made:

<u>Blanket breeding ratio, fusile plus net fissile:</u>

$(T + F_{net})_{blanket} = (T + F_{net})_{Model\ 1} \times$ plena correction x heterogeneous correction

- $(T + F_{net})_{Model\ 1} = 1.13 + 0.70 = 1.83$
- The value of $T + F_{net}$ was found to be insensitive to U233 content.
- Plena correction (from Model 2) = 0.971.
- Heterogeneous correction (Model 3) = 0.943. This correction is sensitive to the U233/Th232 ratio; the value used was calculated at 0.25%, and is taken to be the average value.

$\therefore (T + F_{net})_{blanket} = 1.83 \times 0.971 \times 0.943$

$= 1.83 \times 0.916 = 1.68$

<u>Net fissile breeding ratio (F_{net}):</u>

$(F_{net})_{blanket} = (T + F_{net})_{blanket} - T_{blanket}$

$\therefore (F_{net})_{blanket} = 1.68 - 1.06 = 0.62$

where a blanket tritium breeding ratio of

$$T_{blanket} = T_{reactor} \times \frac{3140}{3000} = 1.01 \times 1.047 = 1.06$$

is needed to sustain the device.

Fissile production rate (G):

$G = 4.32\ (kg/MW_fY) \times P_f\ (MW) \times (F_{net})_{blanket}$

$\therefore G = 4.32 \times 3000 \times 0.62 = 8035$ kg U233/full power year

Blanket energy multiplication, M:

$M = M_{model\ 1} \times$ plena correction $\times$ heterogeneous correction.

At start of cycle (U233 = 0), $M = 1.39 \times 0.98 \times .95 = 1.30$.

At a U233 concentration of 0.25%, $M = 1.66 \times 0.98 \times 1.13 = \underline{1.84}$.

The heterogeneous corrections for M are taken to be 1/2 that calculated because of the infinite nature and lack of structure in the model (No. 3) from which they came. A finite, heterogeneous model is under development to better determine this correction. Preliminary results suggest that an average U233 concentration of 0.5% will give a blanket M of about 2.0.

NUCLEAR DATA UNCERTAINTY

The uncertainty in our estimate of the breeding performance of this blanket is strongly dependent on the uncertainty in the Be (n,2n) reaction rate. For this blanket a 20% drop in the Be (n,2n) rate will reduce the blanket breeding (T + F) ratio by 9% and the net fissile breeding ratio (F_{net}) would drop by 24%. Our calculations of some old Be experiments suggest that a 20% uncertainty in the Be (n,2n) rate is possible.[10] We are planning both thick Be pulse sphere and manganese bath experiments to address this uncertainty.

CONCLUSIONS

Nucleonics analysis shows that our FY82 Be-Li-Th reference blanket will give good breeding (1.68) if the beryllium data uncertainty is not too large and should give reasonably low energy multiplication at an acceptable U233 content. A preliminary assessment of the criticality hazard shows that subcriticality can be maintained without an unacceptable constraint on the buildup of U233 in the Th fuel (< 1.6%).

It must be stressed that the nucleonics appraisal and optimization of this blanket is not complete and work is continuing in order to improve the estimate of nuclear performance. Major improvement is needed in determining energy generation versus U233 content.

A more complete description of this work is given in Ref. 11.

Acknowledgement

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