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NEUTRONICS CALCULATIONS AND COST ESTIMATES FOR FUSION REACTOR BLANKET ASSEMBLIES

Don Steiner

ABSTRACT

We have investigated the tritium breeding potential and the material costs of some thermonuclear blanket assemblies. These assemblies differ from previously proposed assemblies in the following aspects:

(1) Niobium, rather than molybdenum, is employed as the structural material.

(2) Lithium, or a combination of lithium and flibe (lithium-beryllium fluoride), rather than flibe alone, is employed as coolant.

(3) No metallic beryllium is employed; graphite is the only neutron moderator present.

Neutron fluxes and reaction rates were calculated with the ANISN, one dimensional, transport theory code employing an S_8 approximation for the angular flux and a P_3 approximation for the elastic-scatter-source term. In all cases the blanket geometry was idealized as a slab, and one hundred energy groups were employed.

Blanket assemblies containing only lithium as coolant, yield tritium breeding ratios in the range 1.32-1.57. Blanket assemblies containing both lithium and flibe yield attractive tritium breeding ratios (i.e. ~ 1.2 or greater) only when the volume ratio of lithium to flibe is greater than 1:1

It is concluded that the blanket designs considered in this study offe a more attractive combination of tritium breeding ratio and material costs than do the earlier designs.

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NEUTRONICS CALCULATIONS AND COST ESTIMATES FOR FUSION REACTOR BLANKET ASSEMBLIES

Don Steiner

1. Introduction

The purpose of this communication is to present neutronics calculations and cost estimates for some fusion reactor blanket assemblies currently being considered in the fusion feasibility program at Oak Ridge National Laboratory (ORNL).

Previous investigators[1,2] have examined the breeding of tritium in blanket designs consisting of a molybdenum first wall, a molten salt ($2LiF \cdot BeF_2$ called "flibe") coolant, and a beryllium metal or beryllium plus graphite moderator. In such systems beryllium serves both as a moderator and as a source of neutron multiplication through the (n,2n) reaction. Calculated breeding ratios, i.e. the number of tritium atoms produced per 14 mev neutron incident on the first wall, ranged between 1.4 and 1.8.

A recent fusion feasibility study performed at ORNL evolved the following observations with regard to the earlier blanket designs.

(1) Niobium would be preferable to molybdenum as a first wall material because of its superior welding characteristics.

(2) Lithium would be preferable to flibe as a coolant because of its lower cost and superior heat transfer properties. The electromagnetic resistance to lithium flow could be minimized through proper alignment of coolant channels, i.e. parallel to the confining magnetic field lines.

(3) While beryllium is a very efficient moderator and gives excellent neutron multiplication, it is also very expensive and undergoes severe radiation damage.

On the basis of the preceeding observations we propose the following modifications to the earlier blanket designs; (1) the substitution of nobium for molybdenum, (2) the use of lithium or combinations of lithium plus flibe, and (3) the elimination of metallic beryllium and the use of graphite alone. We have investigated the tritium breeding potential and the economics of the modified blanket assemblies. The results of this investigation are presented herein.

2. Calculational Methods

Neutron fluxes and reaction rates were calculated with the ANISN[3] code. ANISN is a one dimensional, multigroup, discrete ordinates transport theory code with anisotropic scattering. The blanket geometry was idealized as a slab, and one hundred energy groups were employed. The angular flux was approximated by an eighth order quadrature (S_8), and the anisotropy of the elastic-scatter-source term was approximated by a third order Legendre expansion (P_3). In calculating the amount of neutron leakage from the blanket it was assumed that the blanket is surrounded by a coil shield which possesses an energy independent albedo of 0.32[2]. Cross sections were taken from the ENDF/B library.

The individual material costs used in estimating total blanket costs are listed in Table 1. Note that these costs are reported in $\$/m^2$-cm, i.e. the cost of a slab of material one square meter in area and one centimeter thick.

Table 1. Material Costs

Material	Cost ($/m^2-cm)
Lithium (natural)	60
Niobium	3,780
Graphite	35
Flibe	423
Beryllium	4,057
Molybdenum	4,590

3. Description of Blanket Assemblies

It is emphasized at this point that the assemblies to be described did not evolve from a detailed optimization procedure. Therefore, the results presented in this communication should be viewed as characteristics representative of the type of systems investigated and not as optimized characteristics.

Two basic blanket designs were considered in this study. These two designs reflect (1) an optimistic outlook, and (2) a conservative outlook with respect to the problem of cooling the blanket. The optimistic outlook assumes that proper design has minimized electromagnetic resistance, and therefore, lithium can be used as coolant throughout the blanket. The conservative outlook assumes that (1) flibe must be used to cool the first wall and (2) combinations of flibe and lithium may be employed to cool the remainder of the blanket.

The essential features of the cases run with the optimistic design, design A, are summarized in Table 2. In those regions designated "coolant + structure" the coolant and structure have been homogenized for neutronics calculations. Cases 1-4 were run in order to study the effect of niobium content on tritium breeding and blanket costs. Case 5 was run in order to compare the tritium breeding potential of systems containing niobium to that of systems containing molybdenum.

The essential features of the cases run with the conservative design, design B, are summarized in Table 3. Cases 6-8 were run in order to study the effect of lithium/flibe content on tritium breeding and blanket costs. Table 3 also includes the description of an assembly which contains metallic beryllium. This case, case 9, was run in order to compare the breeding potential and economics of assemblies with and without metallic beryllium.

4. Results and Discussion

The ANISN code was used to calculate spatially dependent reaction rates for the cases described in Tables 2 and 3. In these calculations the reaction rates were normalized to a source of one 14 mev neutron incident on the first wall. The results of the neutronics calculations are summarized in Table 4, where T_6 is the tritium breeding ratio in Li^6, T_7 is the tritium breeding ratio in Li^7, T is the sum of T_6 and T_7, and L is the neutron leakage. Table 4 also contains the cost estimates (in $\$/m^2$) for each of the assemblies investigated.

Table 2. Summary Description of Cases Run With Design A

Region Number	Description of Region	Thickness of Region (cm)	Materials in Regions				
			Case 1	Case 2	Case 3	Case 4	Case 5
1	First Wall	0.5	Niobium	Niobium	Niobium	Niobium	Molybdenum
2	First Wall Coolant	3.0	Lithium	Lithium	Lithium	Lithium	Lithium
3	Second Wall	0.5	Niobium	Niobium	Niobium	Niobium	Molybdenum
4	Coolant + Structure	60.0	98% Lithium 2% Niobium	96% Lithium 4% Niobium	94% Lithium 6% Niobium	92% Lithium 8% Niobium	98% Lithium 2% Molybdenum
5	Moderator	30.0	Graphite	Graphite	Graphite	Graphite	Graphite
6	Coolant + Structure	6.0	98% Lithium 2% Niobium	96% Lithium 4% Niobium	94% Lithium 6% Niobium	92% Lithium 8% Niobium	98% Lithium 2% Molybdenum
	Total	100cm.					

Note: All percentages are volume percentages.

Table 3. Summary Description of Cases Run With Design B and of Case 9

Region Number	Description of Region	Thickness Of Region (cm)	Materials in Regions Case 6	Case 7	Case 8	Thickness Of Region (cm)	Materials Case 9
1	First Wall	0.5	Niobium	Niobium	Niobium	0.5	Niobium
2	First Wall Coolant	5.0	Flibe	Flibe	Flibe	3.0	Lithium
3	Second Wall	0.5	Niobium	Niobium	Niobium	0.5	Niobium
4	Coolant + Structure	9.34	98% Lithium 2% Niobium	98% Lithium 2% Niobium	Flibe	5.0	30% Lithium 60% Beryllium 10% Niobium
5	Coolant + Structure	9.33	98% Lithium 2% Niobium	Flibe	Flibe	3.0	90% Lithium 10% Niobium
6	Coolant + Structure	9.33	98% Lithium 2% Niobium	98% Lithium 2% Niobium	Flibe	5.0	30% Lithium 60% Beryllium 10% Niobium
7	Coolant + Structure	9.33	98% Lithium 2% Niobium	Flibe	Flibe	3.0	90% Lithium 10% Niobium
8	Coolant + Structure	9.33	98% Lithium 2% Niobium	98% Lithium 2% Niobium	Flibe	5.0	30% Lithium 60% Beryllium 10% Niobium
9	Coolant + Structure	9.34	98% Lithium 2% Niobium	Flibe	Flibe	3.0	90% Lithium 10% Niobium
10	Moderator	40.0	Graphite	Graphite	Graphite	40.0	Graphite
11	Coolant + Structure	3.0	98% Lithium 2% Niobium	98% Lithium 2% Niobium	Flibe	6.0	90% Lithium 10% Niobium
	Total	105cm			Total	74cm	

Table 4. Summary of Neutronics Calculations and Cost Estimates

Case Number	Neutronics*				Cost Estimates ($/m²)						
	T_6	T_7	T	L	$C_{Lithium}$	C_{Flibe}	$C_{Niobium}$	$C_{Molybdenum}$	$C_{Beryllium}$	$C_{Graphite}$	C_{Total}
1	0.91	0.66	1.57	0.030	4,061		8,770			1,050	13,881
2	0.85	0.63	1.48	0.027	3,982		13,760			1,050	18,792
3	0.79	0.60	1.39	0.024	3,902		18,749			1,050	23,701
4	0.74	0.58	1.32	0.022	3,823		23,738			1,050	28,611
5	1.13	0.57	1.70	0.029	4,061			10,648		1,050	15,759
6	0.87	0.40	1.27	0.013	3,469	2,115	8,240			1,400	15,224
7	0.87	0.29	1.16	0.003	1,823	13,959	6,124			1,400	23,306
8	0.87	0.16	1.03	0.001		27,072	3,780			1,400	32,252
9	1.06	0.30	1.36	0.032	1,260		15,120		36,513	1,400	54,293

*Basis: One 14 mev neutron incident on the first wall. T_6 is the tritium breeding ratio in Li^6, T_7 is the tritium breeding ratio in Li^7, T is the sum of T_6 and T_7, and L is the neutron leakage.

The following observations are made on the basis of these results.

(1) Attractive tritium breeding ratios, e.g. ~ 1.4, can be achieved in systems which do not contain metallic beryllium. This result is explained as follows. Tritium production occurs both in Li^6, for which the reaction cross section varies inversely with the neutron velocity below ~ 0.3 mev, and in Li^7, for which the Li reaction cross section has a threshold at ~ 2.8 mev. Thus, the $Li^6(n,\alpha t)$ reaction is favored at low neutron energies while the Li^7 $(n,\alpha tn')$ reaction is favored at high neutron energies. In systems containing metallic beryllium the bulk of the tritium production occurs in Li^6 due to the effectiveness of beryllium as a neutron moderator. The removal of beryllium shifts the neutron spectrum to higher energies and therefore leads to a reduction in Li^6 tritium production; however, this reduction is compensated by a significant increase in Li^7 tritium production, e.g. compare cases 3 and 9. Also, it should be noted that each Li^6 $(n,\alpha t)$ reaction consumes the incident neutron while each $Li^7(n,\alpha tn')$ only degrades the energy of the incident neutron. Thus, neutron multiplication is not essential for tritium breeding in systems having a significant amount of Li^7 $(n,\alpha tn')$ reactions.

(2) The tritium breeding ratios for cases 3 and 9 are nearly equal, however, the total blanket costs for case 3, which does not contain metallic beryllium, is about 60% lower than the total blanket cost for case 9, which does contain metallic beryllium. At an energy flux of 10 Mw/m^2 through the first wall, the removal of metallic beryllium represents a saving of $\sim 10^8$\$ for a system producing 30,000 Mwth.

(3) It is desirable to limit the niobium content in the the blanket because niobium is both expensive and deleterious to tritium breeding,

e.g. compare cases 1-4. Structural stability requirements will dictate the amount of niobium needed. Preliminary investigations indicate that case 2 represents a reasonable niobium content.

(4) The tritium breeding potential of assemblies containing niobium is somewhat inferior to that of systems containing molybdenum, e.g. compare cases 1 and 5. This is due to two factors; (a) the (n,2n) cross section of niobium is about 75% lower than that of molybdenum, and (b) non-productive neutron absorptions in niobium are ~ 10% greater than are those in molybdenum.

(5) If flibe, rather than lithium, is used as the first wall coolant, the tritium breeding ratio is reduced considerably, e.g., compare cases 1 and 6. This reduction in breeding ratio is due primarily to a reduction in ^{7}Li tritium production, and is a result of inelastic scattering in fluorine. Acceptable breeding ratios can be achieved with a flibe first wall coolant only when significant amounts of lithium are present in the remainder of the blanket.

5. Conclusions

We have investigated the tritium breeding potential and the material costs of some thermonuclear blanket assemblies. These assemblies differ from previously proposed assemblies in the following aspects:

(1) Niobium, rather than molybdenum, is employed as the structural material.

(2) Lithium, or a combination of lithium and flibe, rather than flibe alone, is employed as coolant.

(3) No metallic beryllium is present.

It is concluded that the blanket designs considered in this study offer a more attractive combination of tritium breeding ratio and material costs than do the earlier designs.

REFERENCES

1. George I. Bell, "Neutron Blanket Calculations for Thermonuclear Reactors," Los Alamos Scientific Laboratory Report LA-3385-MS (1965).

2. Albert J. Impink Jr., "Neutron Economy in Fusion Reactor Blanket Assemblies," Massachusetts Institute of Technology Research Laboratory of Electronics Technical Report 434 (1965).

3. Ward W. Engle Jr., "A Users Manual for ANISN: A One Dimensional Discrete Ordinates Transport Code With Anisotropic Scattering," Rep. K-1693, Oak Ridge Gaseous Diffusion Plant (1967).

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