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ABSTRACT

The breeding potentials of various neutron blankets surrounding a pulsed thermonuclear reactor have been calculated using multigroup methods. A basic lithium blanket containing up to 15 volume percent niobium was found to give marginal breeding. For such Nb concentrations the neutron flux depression at Nb resonances should be taken into account in devising multigroup cross sections; this resonance self-shielding increases the triton production by ~10% in the basic blanket. Several modifications of the basic design were found to give improved breeding, in which the ratio of tritons produced to tritons burned, in making 14 MeV neutrons, is equal to or greater than 1.20. These include (a) replacement of Nb by Mo and Zr, (b) use of lithium enriched in ^{6}Li, and (c) addition of hydrogen to the blanket. The displacement of lithium by beryllium does not appear attractive. Thus, a variety of options are available to obtain satisfactory breeding from a lithium blanket containing substantial amounts of structural material.

INTRODUCTION

In LA-3385-MS [1], hereafter referred to as I, calculations were reported on the neutron economy in various hypothetical blankets for pulsed thermonuclear reactors. Consideration was given to blankets containing lithium, beryllium, beryllium carbide, and "flibe" (a mixture of the fluorides of lithium and beryllium). In each problem, 14 MeV neutrons were started in a central region of thermonuclear fuel and for each blanket the triton production and neutron leakage were determined. The breeding potential of the blanket was assessed in terms of T_6 (number of tritons produced by ^{6}Li(n,T)α reactions, per 14 MeV neutron), T_7 (number of tritons produced by ^{7}Li(n,n′T)α reactions per 14 MeV neutron), and L (the number of neutrons leaking out of the system per 14 MeV neutron). A number of configurations were identified having satisfactory breeding potentials, i.e., values of $T_6 + T_7 + L$ substantially in excess of unity.

Recent studies by Fred Ribe and others [2] have indicated that for structural reasons it would be desirable to include a considerable amount of niobium or molybdenum in the blanket. Since these materials are fairly effective in capturing neutrons, it seemed desirable to investigate their effects on blanket neutron economy. Previous studies by Steiner [3] had indicated that the required amounts of Nb might seriously degrade the breeding potential.

The calculational method was the same as used in I. The geometry was approximated by an infinitely long cylinder and the neutron transport was computed using the DTF-IV code [4] with 25 energy groups, the S_4 and transport approximations. For calculations involving hydrogen, linearly anisotropic scattering was allowed. Cross sections for

^{6}Li, ^{7}Li, and Be were the same as used in I while for Cu, Mo, Nb, and Zr the following cross sections evaluations were used [5]

Cu	UK	evaluation	1967
Mo	LRL	evaluation	1965
Nb	LRL	evaluation	1965
Zr	UK	evaluation	1965

However, the Mo (n, γ) cross sections were adjusted to the values shown in table III, to take into account data in [6].

During the course of calculations on blankets containing Nb, it became apparent that an appreciable fraction of the neutrons was being absorbed in niobium resonances. Therefore, a separate estimate was made of the flux reduction at resonance energies, i. e., resonance self-shielding, which had not been taken into account in devising the niobium cross sections. These self-shielding estimates are described in the following section and were used in drawing up a set of self-shielded (n,γ) cross sections as will be explained.

RESONANCE SELF-SHIELDING

In blankets containing lithium and niobium, neutrons are captured by niobium mostly in the energy range 1 keV $\le$ E $\le$ 100 keV, hence mostly in s and p wave resonances. Resonance parameters have been measured for only a few of these resonances at the lower energies. It is necessary, therefore, to estimate the resonance parameters for resonances throughout this energy region in order to obtain the resonance self-shielding effects. This has been done in the following way.

First of all, from the measured resonance parameters at low energies it is possible to deduce some average s-wave resonance parameters and then from average cross sections, average p-wave parameters can be found. Care is required since an unusually large proportion of the low energy resonances are p-wave, but recent experiments [7, 8, 9] have led to a consistent picture. From these we have adopted the following values:

s_o = s-wave strength function = 0.4×10^{-4}

s_1 = p-wave strength function = 5×10^{-4}

Γ_γ = 200 meV

D_{obs} = observed s-wave average level spacing = 100 eV

The target nucleus, ^{93}Nb, has spin and parity $9/2^+$. Thus, the states of ^{94}Nb which can be reached by s-wave capture are 4^+ and 5^+, while 3^-, 4^-, 5^-, and 6^- states can be reached by p-wave capture. Most of these states are expected to have comparable average level spacing [10]. In particular, the 4^+ and 5^+ states will have comparable spacings; hence, for each it is assumed that D = 200 eV. Moreover, this same spacing is assumed for the four kinds of p-wave levels. From the above value of D, together with the value of the s-wave strength function, it follows that for the s-wave resonances, $\overline{\Gamma_n^o}$ = 8 meV and thus $\overline{\Gamma}_n$ = .008 $\sqrt{E}$ eV where E is the neutron energy in eV. Similarly for the p-wave levels, it was assumed that

$$\overline{\Gamma}_n = .1 \sqrt{E} \frac{(R/\lambda\!\!\!^-)^2}{1 + (R/\lambda\!\!\!^-)^2} \text{ eV} \quad ,$$

where R, the nuclear radius was taken to be 5.9 × 10^{-13} cm and $\lambda\!\!\!^-$, the neutron wavelength is 4.55 × 10^{-10} $E^{-1/2}$ cm.

As a check on the above parameters the average capture cross section was then computed for niobium in the energy range 1 keV $\le$ E $\le$ 100 keV. The following equations were used, for the cross sections averaged over many resonances,

$$\langle\sigma_{n,\gamma}(E)\rangle_{s\text{-wave}} = 2\pi^2\lambda\!\!\!^-{}^2 \frac{\overline{\Gamma}_n\Gamma_\gamma}{(\overline{\Gamma}_n + \Gamma_\gamma)D} S_1\left(\frac{\Gamma_\gamma}{\overline{\Gamma}_n}\right) ; \quad (1)$$

where S_1 is the function

$$S_1\left(\frac{\Gamma_\gamma}{\overline{\Gamma}_n}\right) = \frac{\left\langle \frac{\Gamma_n\Gamma_\gamma}{\Gamma_n + \Gamma_\gamma}\right\rangle}{\frac{\overline{\Gamma}_n\Gamma_\gamma}{\overline{\Gamma}_n + \Gamma_\gamma}} \quad (2)$$

which has been graphed by Lane and Lynn [11]. Upon introducing the values given above for $\lambda\!\!\!^-{}^2$, $\overline{\Gamma}_n$, Γ_γ and D, equation (1) becomes

$$\langle\sigma_{n,\gamma}\rangle_{s\text{-wave}} = \frac{163}{\sqrt{E}} \frac{1}{1 + .04\sqrt{E}} S_1\left(\frac{1}{.04\sqrt{E}}\right) . \quad (3)$$

For the p-wave resonances, it was assumed that D and $\overline{\Gamma}_n$ were the same for resonances of the four available spins, and that each level had but one open neutron channel. The average capture cross section is then,

$$\langle\sigma_{n,\gamma}\rangle_{p\text{-wave}} = 6\pi^2\lambda^2 \frac{\bar{\Gamma}_n}{D} \frac{1}{1+\frac{\bar{\Gamma}_n}{\Gamma_\gamma}} S_1\left(\frac{\Gamma_\gamma}{\bar{\Gamma}_n}\right) \quad . \qquad (4)$$

Average capture cross sections, obtained from equations (3) and (4) are given in Table I. The computed values are in good agreement (±20%) with experimental results in [6].

Table I. Computed Average Capture Cross Sections for Nb

Neutron Energy	$\langle\sigma_{n,\gamma}\rangle_{s\text{-wave}}$	$\langle\sigma_{n,\gamma}\rangle_{p\text{-wave}}$	sum = $\langle\sigma_{n,\gamma}\rangle$
1 keV	1.54 b	0.30 b	1.84 b
3	0.62	0.44	1.06
10	0.23	0.39	0.62
30	0.09	0.24	0.33
100	0.03	0.10	0.13

Consider neutrons being moderated in a mixture of lithium and niobium. The neutron flux will be depressed at the niobium resonance energies because of the correspondingly high niobium cross sections. This depression may be estimated by using the theoretical methods which have been devised for treating similar problems in natural uranium fission reactors [12,13]. An effective cross section, $\tilde{\sigma}_{n,\gamma}(E)$, and a self-shielding factor, ssf(E), may be defined from the relation

$$\tilde{\sigma}_{n,\gamma}(E) = \frac{\int \sigma_{n,\gamma}(E')\varphi(E')dE'}{\int \varphi(E')dE'} = \text{ssf}(E)\langle\sigma_{n,\gamma}(E)\rangle \, , \quad (5)$$

where the integrals extend over many resonances around the energy E, and φ is the neutron flux.

In our energy region, the narrow resonance or NR approximation may be used for estimating φ(E). In addition we have used the rational approximation to the escape probability [13,14], neglected interference between resonance and potential scattering [13], and used average resonance parameters at the energy E. None of these approximations are required; for example the computations could be made with a detailed numerical code such as TUZ [15]. However, it was felt that for the present estimates a simpler approach based on the above approximations should suffice. With these approximations the self-shielding factor for a resonance at energy E is given by:

$$\text{ssf} = \frac{2}{\pi}\frac{\sigma_p}{\sigma_o} J\left(\zeta, \frac{\sigma_p}{\sigma_o}\right) \quad . \qquad (6)$$

Here σ_o is the peak resonance cross section, namely, for s-waves

$$\sigma_o = \frac{2.6 \times 10^6}{E} g \frac{\Gamma_n}{\Gamma} b \quad , \qquad (7)$$

σ_p is an effective potential scattering cross section, taken (for the inner third of the Nb-Li lattice of problem Nb 7a) to be 15 barns. In addition ζ is the ratio of natural to Doppler width,

$$\zeta = \frac{\Gamma}{2}\sqrt{\frac{A}{kTE}}$$

while J is a tabulated Doppler function which was taken from [16]. The statistical weight factor was taken to be 1/2 for s-wave neutrons. (Equation (7) was also used for the p-wave resonances with constants corresponding to g = 1.)

Equation (6) gives a self-shielding factor for a single resonance at energy E. If, however, that resonance is given average parameters, the result may be used as a factor by which the average cross section is to be reduced to account for the flux depression, i. e., as defined in equation (5).

Using the above procedure, self-shielding factors were computed for the s-wave and p-wave resonances and by combining the results, for the (n,γ) cross section. Results are given in Table II.

Table II

Neutron Energy	Self-Shielding Factors		
	s-wave	p-wave	$\sigma_{n,\gamma}$
1 keV	0.20	0.77	0.29
3	0.37	0.77	0.54
10	0.65	0.80	0.72
30	0.80	0.77	0.78
100	0.90	0.77	0.80

These factors were used in the following way. For calculations with "self-shielded" Nb cross sections the average or multigroup (n,γ) cross sections for niobium were reduced by multiplication by the above factors.*

Evidently a large number of approximations were made in deriving the above factors. Inasmuch as (1) the effects of self-shielding are not found to be of decisive importance and (2) obtaining more

*See, however, the footnote to Table III.

reliable values would be considerably more difficult and would require a detailed engineering design, it was felt that the above estimates suffice for present purposes.

THE CALCULATIONS

In I some of the more significant neutron cross sections were given. These were also used in the present calculations, except that the Cu (n,2n) cross section was taken to be 0.64 for the 14 MeV neutrons. The important (n,γ) cross sections are given in Table III for molybdenum and niobium.

Table III. (n,γ) Cross Sections

Energy Group	Energy Range	Mo	Nb No Self-Shielding	Nb With Self-Shielding
8	580 - 900 keV	0.04 b	0.027 b	0.027 b
9	370 - 580	0.045	0.049	0.049
10	240 - 370	0.050	0.06	0.06
11	150 - 240	0.060	0.071	0.071
12	100 - 150	0.070	0.083	0.083
13	31.6 - 100	0.100	0.159	0.12
14	10 - 31.6	0.210	0.44	0.30
15	3.16 - 10	0.50	0.56	0.56 (a)
16	1 - 3.16	0.70	0.94	0.60 (a)
17	0.316 - 1	1.5	1.56	0.50
18	0.1 - 0.316	1.5	1.62	0.50

(a) To groups (15) and (16) it was felt that the Nb cross sections without self-shielding were too low and the self-shielding factors of Table II were applied to the data in Reference 6, thereby yielding these values.

In all the calculations, 14 MeV neutrons were started uniformly and isotropically in a central cylinder having a radius of 10 cm. The radial region from 10 cm to 13 cm was taken to be copper; this material carries the current to drive the pulsed thermonuclear reactor. Surrounding the copper is a blanket in which the fast neutrons are to be converted into tritons. The blanket was chosen to be 1.5 meters in thickness and to contain various ribs and webs of structural material [2] which are designed to transmit the stresses from the copper to an outer shell of steel. The blanket was divided into three radial regions as follows:

	Volume of Ribs	Volume of Webs
$13 \le r \le 63$ cm	6.92%	7.86%
$63 \le r \le 113$	2.97%	6.17%
$113 \le r \le 163$	1.90%	5.75%

Atomic densities for various materials were the same as in I. In addition, for Nb and Zr, respectively, the densities 0.0545 and 0.0425 $\times 10^{24}$ atoms/cm^3 were used.

RESULTS

Some results of the calculations, indicating the neutron economy to be expected in various blanket configurations are given in Table IV.

Table IV. Triton Production per 14 MeV Neutron

Geometry: Cylindrical; $0 \le r \le 10$ cm Neutron Source; $10 \le r \le 13$ cm, Cu; $13 \le r \le 163$ cm blanket as described on page 6

Notation: T_6, tritons from $^6Li(n,\alpha)T$; T_7, tritons from $^7Li(n,n'T)\alpha$; L, leakage; $T = T_6 + T_7 + L$; Abs, net neutron absorption in blanket ribs and webs. Nb = niobium without self-shielding, Nb* = niobium with self-shielding.

Problem Number	Blanket Materials: Ribs	Webs	Bulk	T_6	T_7	L	T	Abs
Nb 1a	Nb	Nb	Li	0.79	0.22	0.03	1.03	0.30
Nb 1b	Nb*	Nb*	Li	0.84	0.22	0.03	1.09	0.24
Nb 2	Nb	Nb	Li (20% Li^6)	1.00	0.17	0.01	1.18	0.12
Mo 1	Mo	Mo	Li	0.86	0.20	0.05	1.10	0.22
Mo 2	Mo	Mo	Li (20% Li^6)	1.10	0.17	0.01	1.28	0.09
Nb 7a	Nb	Zr	Li	0.90	0.23	0.05	1.18	0.17
Nb 7b	Nb*	Zr	Li	0.93	0.23	0.05	1.21	0.14
Mo 7	Mo	Zr	Li	0.95	0.23	0.05	1.22	0.12
Nb 8	Nb*	Zr	Li + 0.005 H (a)	1.03	0.21	0.005	1.24	0.08
Nb 5	Nb	Nb	Li + Be (b)	0.79	0.14	0.02	0.95	0.42

(a) Hydrogen at a density of 0.005 $\times 10^{24}$ atoms/cm^3 was added to the whole blanket

(b) In the inner 10 cm of blanket, Be was inserted to take up half the volume, displacing lithium.

A number of features may be observed from these calculations:

(1) The first problem run, Nb 1a, indicates a distinctly marginal breeding potential (T = 1.03), the difficulty being that the niobium is absorbing too many neutrons, i. e., more than a quarter of the total. The remaining problems respresent efforts to cut down this niobium absorption.

(2) In Nb 1b it is seen that the breeding potential is enhanced by including the self-shielding of niobium, T increasing by 0.06. Actually the effect of self-shielding per se is probably more like an increase of 0.10 in T because of the effect explained in the footnote to Table III, and because the value of σ_p(15 b) is somewhat too large for the lattice in problem 1a.

(3) In Nb 2 it is seen that T increases to 1.18 if lithium enriched to 20% in ^{6}Li is used in the blanket so that a larger fraction of the neutrons are captured by ^{6}Li. Actually, the bulk of this increase (relative to Nb 1a) would be realized if only the inner third of the blanket contained enriched lithium.

(4) In problems Mo 1 and Mo 2, it is seen that molybdenum is neutronically superior to niobium. A larger (n,2n) cross section and somewhat smaller (n,γ) cross section are responsible for this

superiority.

(5) It was felt that zirconium, by virtue of its small (n,γ) cross section, [17] would be a better blanket material than either niobium or molybdenum. However, structural considerations [2] make it unlikely that Zr could be used for the ribs, though probably Zr would be a satisfactory material for the webs. In problems Nb 7 the beneficial effect of using Zr webs is seen. In these problems there is less absorption than in Nb 1; therefore, the effect of self-shielding is relatively small. Problem Mo 7 shows that the difference between molybdenum and niobium is also much reduced when zirconium webs are used.

(6) Since the niobium self-shielding factors are smaller at lower neutron energies (cf Table III) and the niobium thus does not compete with ^{6}Li as effectively at low energies in neutron capture, it was of interest to examine the effect of lowering the neutron energy spectrum. This was accomplished by adding a small amount of hydrogen to the blanket in Nb 8. The net effect, as compared with Nb 7b was mildly beneficial. In a configuration with more niobium, such as Nb 1a, the effect would be considerably larger. In practice the hydrogen might be added in zirconium hydride.

(7) In problem Nb 5 it is seen that the effect of displacing lithium by beryllium is unfavorable. In this instance the reason is that most of the added neutrons (caused by (n,2n) reactions on beryllium) are absorbed by niobium. While somewhat different arrangements might be more advantageous, it does not appear that the use of beryllium in these heavily poisoned blankets is attractive.

(8) Effects of self-shielding were not investigated for molybdenum. The calculation would have been more complicated for molybdenum than for niobium, since the seven stable isotopes of molybdenum should be considered separately. However, it is believed that the relative reductions in absorption caused by self-shielding should be similar to those observed for Nb. The reason is that the level spacing for the even-even (target) isotopes of Mo should be larger than for ^{93}Nb [10]. Hence Γ_n should be larger and the resonances will thus be more pronounced. This effect will partly compensate for the lower abundance of any particular isotope.

CONCLUSIONS

The breeding potential of a lithium blanket is adversely affected by substantial quantities of niobium in the blanket. For a particular blanket configuration having about 15 volume percent Nb near the neutron source, the breeding is marginal. For such Nb concentrations the flux depression at Nb resonances should be taken into account in devising multigroup cross sections; this resonance self-shielding increases the triton production by ~10% in the above blanket.

Several modifications of the original design offer improved breeding with T $\geq$ 1.20. These include (a) replacement of Nb by Mo and Zr, (b) use of lithium enriched in ^{6}Li, and (c) addition of H. The displacement of lithium by beryllium does not seem attractive.

It is thus seen that a variety of options are open to a blanket designer in order to obtain satisfactory breeding from a lithium blanket containing substantial quantities of structural material.

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