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NEUTRONIC IMPLICATIONS OF LEAD-LITHIUM BLANKETS*

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ABSTRACT

Lead-lithium alloys have been proposed for use in several conceptual blanket designs for both inertial and magnetic confinement fusion reactors. In most cases, $Pb_{83}Li_{17}$, a eutectic with a melting point of $235^{\circ}C$, is the chosen composition. The primary reasons for using $Pb_{83}Li_{17}$ instead of Li as the tritium breeding material are the perceived safety advantages, low tritium solubility, and favorable neutronic characteristics. This paper describes the neutronic characteristics of $Pb_{83}Li_{17}$ blankets with emphasis on the enhanced neutron leakage through chamber ports and the degradation in blanket performance parameters that occurs as a result of the enhanced leakage.

INTRODUCTION

Lead-lithium alloys have been specified as the tritium breeding material in conceptual designs of inertial fusion reactors,^{1,2} mirror machines³ and Tokamaks.^{4,5} The physical, chemical and nuclear properties of lead-lithium alloys have been widely discussed (see Refs. 6 and 7 for example). The most frequently selected alloy is the eutectic composition, $Pb_{83}Li_{17}$. This alloy, with a melting point of $235^{\circ}C$, can readily be used as the primary coolant as well as the breeding material. One principal advantage of $Pb_{83}Li_{17}$ over Li is that it is relatively inert with water. Also the solubility of tritium in $Pb_{83}Li_{17}$ is very low which implies a low tritium inventory in the blanket/coolant.

A tritium breeding ratio greater than one is easily achieved with $Pb_{83}Li_{17}$ since lead is an effective neutron multiplier with an $(n,2n)$ cross section of ~ 2 barns at 14 MeV. Most of the tritium breeding occurs via exothermic ${}^6Li(n,T)\alpha$ reactions. This results in a

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substantial neutron energy multiplication with > 18 MeV deposited per 14 MeV fusion neutron. Unfortunately, there are also some unfavorable neutronic implications of using lead-lithium blankets. Since Pb is a poor neutron moderator, hundreds of elastic scattering reactions take place per DT-neutron. This results in a large neutron current directed back into the vacuum chamber. When chamber ports (i.e., for laser beams or ion beams) are included in the neutronics calculations, the results show that the total neutron leakage through the ports is much greater than the direct loss of 14.1 MeV neutrons. The enhanced leakage is most pronounced for blanket materials that result in a high ratio of scattering reactions to absorption reactions and in a high neutron multiplication.⁸ The lead-lithium eutectic, $Pb_{83}Li_{17}$, is such a material. The high neutron leakage results in degraded blanket performance in terms of both tritium breeding and neutron energy deposition. The magnitude of these effects is quantified for a simple inertial fusion reactor geometry. TARTNP,⁹ a coupled neutron-photon Monte Carlo Code, and ENDL,¹⁰ the 175-group Livermore nuclear data library, were used in these calculations.

CHAMBER MODEL

The chamber configuration modeled to investigate these effects is shown in Fig. 1. It is a spherical inertial confinement fusion chamber with the beam ports represented by two diametrically opposed, conical penetrations through the blanket. The total solid angle subtended by the two ports is Ω . The compressed DT fuel of the inertial fusion pellet is not included in this model. Instead, a point source of 14.1 MeV neutrons is located at the origin so that the leakage of 14.1 MeV neutrons, expressed as neutrons/source neutron, is equal to $\Omega/4\pi$. The blanket consists of a 70-cm-thick liquid-metal region at a radius of 5.0 m followed by a 30-cm-thick graphite reflector and a 5-cm-thick steel vessel wall. The chamber configuration roughly represents the JADE chamber described by Monsler.² The material compositions of the various regions are described in Table 1. The liquid-metal blanket region is 90 vol.% $Pb_{83}Li_{17}$ (with natural lithium) and 10 vol.% ferritic steel (2.25 Cr-1 Mo).

Fig. 1 Chamber configuration modeled to investigate the effects of neutron leakage through beam ports.

Table I. Description of neutronics model.

Region Description	Region Composition	Elements	Atomic Densities (at/b·cm)
Lead-lithium blanket	90 vol% $\text{Pb}_{83}\text{Li}_{17}$ 10 vol% ferritic steel $\rho(\text{Pb}_{83}\text{Li}_{17})=9.21 \text{ g/cm}^3$ $\rho(\text{steel})=7.86 \text{ g/cm}^3$	^6Li	0.000364
		^7Li	0.004534
		Pb	0.023913
		Cr	0.000205
		Fe	0.008200
		Mo	0.000049
Graphite reflector	100% graphite $\rho=1.70 \text{ g/cm}^3$	^{12}C	0.085141
Vessel wall	100% ferritic steel $\rho=7.86 \text{ g/cm}^3$	Cr	0.002048
		Fe	0.082000
		Mo	0.000493

RESULTS

Base Case

As a point of reference, a neutronics calculation was run for a blanket without beam ports, $\Omega = 0$. The tritium breeding ratio was 1.128 with ${}^6\text{Li}(n,T)\alpha$ and ${}^7\text{Li}(n,n'T)\alpha$ contributions of 1.104 and 0.024 respectively. The total energy deposited in the blanket as a result of neutron interactions was 18.77 MeV per DT-neutron.

A good indicator of how sensitive the results will be to the inclusion of beam ports in the calculation is the number of neutrons per DT-neutron that reenter the vacuum cavity. With this blanket, the result is 7.80 neutrons per DT-neutron. (For comparison, the result with a Li blanket is 1.32). Therefore, the probability of neutron leakage through the beam ports is high and the blanket performance degrades rapidly as the size of the ports is increased.

The large neutron flow back into the vacuum cavity is primarily the result of the extremely large number of elastic scattering reactions; there are 366 per DT-neutron. The vast majority of these (297) occur with Pb. Another contributing factor is neutron multiplication; there are 0.782 $(n,2n)$ reactions per DT-neutron, 0.738 of which are with Pb. Since this reaction is only possible with high energy neutrons ($E > 7.4$ MeV for ${}^{208}\text{Pb}$), most occur within the first ~ 20 cm of the blanket. The probability of the secondary neutrons reentering the vacuum cavity and subsequently escaping through the ports is therefore higher than if the $(n,2n)$ reaction density were uniform throughout the liquid-metal region.

Leakage Through Beam Ports

To determine the neutron leakage through the beam ports as a function of their size, four additional calculations were run. In these calculations, the solid angle fractions subtended by the ports, $\Omega/4\pi$, were 0.02, 0.04, 0.07 and 0.10.

The results are given in Table 2 and plotted in Fig. 2. The dashed line labeled " $\Omega/4\pi$ " is the geometrically predicted neutron leakage and is equal to the direct loss of 14.1 MeV neutrons. The total neutron leakage through the ports is ~ 6 -7 times higher than the direct loss.

Table II. Results of neutronics calculations for a $Pb_{83}Li_{17}$ blanket
(all values per DT-neutron).

$\Omega/4\pi$	Beam Port Leakage	T_6	T_7	T_T	Neutron Energy Deposited (MeV)	Neutron Energy Leakage (MeV)
0	0	1.104	0.024	1.128	18.77	-
0.02	0.144 (3.6) ^a	0.997	0.023	1.020	17.48	0.34
0.04	0.261 (1.9)	0.918	0.022	0.940	16.55	0.69
0.07	0.427 (1.8)	0.798	0.022	0.820	15.28	1.18
0.10	0.556 (1.3)	0.704	0.021	0.725	14.20	1.67

^a Values in parenthesis are percent standard deviation.

Fig. 2 Total neutron leakage per DT-neutron as a function of the solid angle subtended by the ports. $\Omega/4\pi$ equals the direct loss of 14.1 MeV neutrons.

The energy distribution of the neutrons leaking through the ports is shown in Fig. 3. Each bar indicates the number of leakage neutrons with energies greater than the energy group lower limit. The majority of the additional leakage neutrons (i.e., excluding the 14.1-MeV neutrons) have energies > 0.1 MeV.

Tritium Breeding Ratio

The tritium breeding results are also listed in Table 2. The columns labeled T_6 and T_7 are the number of ${}^6\text{Li}(n,T)\alpha$ and ${}^7\text{Li}(n,n'T)\alpha$ reactions per DT-neutron, respectively. The tritium breeding ratio, T_T , is the sum of T_6 and T_7 . With no beam ports, the $\text{Pb}_{83}\text{Li}_{17}$ blanket has a tritium breeding ratio of 1.128. Including ports that subtend $> 2\%$ of the blanket reduces the breeding ratio to below breakeven.

The ratio $T_T(\Omega)/T_T(0)$ is plotted in Fig. 4, where $T_T(0)$ is the tritium breeding ratio for the case without ports. Also shown in Fig. 4 is the blanket coverage fraction, $1-(\Omega/4\pi)$. This is the expected breeding performance in the absence of enhanced neutron leakage. The breeding ratio decreases at 4 times the expected rate.

In order to obtain a tritium breeding ratio greater than 1.0 with $\Omega/4\pi > 2\%$, the lithium must be enriched in ${}^6\text{Li}$. For example, with $\Omega/4\pi = 0.04$, enriching the lithium to 25% in ${}^6\text{Li}$ increases the tritium breeding ratio from 0.940 to 1.206. Most of this increase results from the fact that ${}^6\text{Li}$ absorbs some neutrons previously captured by Pb or Fe. The beam port leakage decreases only slightly from 0.261 to 0.217.

Neutron Energy Deposition

The final two columns of Table 2 give the neutron energy deposited in the blanket and the neutron energy leakage. The neutron energy leakage is dominated by the direct loss of 14.1 MeV neutrons; less than 20% of the energy leakage is carried by the additional neutrons.

The energy multiplication of the $\text{Pb}_{83}\text{Li}_{17}$ blanket is quite high with 18.77 MeV deposited per 14.1 MeV DT-neutron. This energy deposition decreases rapidly with decreasing blanket coverage. Figure 5 is a plot

Fig. 3 Energy distribution of neutrons leaking through ports for $\Omega/4\pi = 0.1$.

Fig. 4 Normalized tritium breeding ratio as a function of the open solid angle fraction. The dashed line is the geometrically predicted scaling.

Fig. 5 Normalized neutron energy deposition in the blanket as a function of the open solid angle fraction. The dashed line is the geometrically predicted scaling.

of the ratio $E_D(\Omega)/E_D(0)$, where $E_D(0)$ is the energy deposition for the case without ports. The dashed line is the geometrically expected rate of decrease in energy deposition. The energy deposition in the blanket decreases at ~ 2.5 - 3.5 times the expected rate, with the high end of this range corresponding to $\Omega/4\pi < 0.02$.

It is important to note that the decrease in blanket energy deposition associated with enhanced neutron leakage is primarily the result of lost opportunities for exothermic reactions within the blanket. The actual energy carried out of the chamber by the additional leakage neutrons is small compared to the energy that would have been released within the blanket had these neutrons undergone ${}^6\text{Li}(n,T)\alpha$ or $\text{Fe}(n,\gamma)$ reactions, for example, which release 4.8 MeV and 7.6 MeV respectively.

CONCLUSIONS

The lead-lithium eutectic, $\text{Pb}_{83}\text{Li}_{17}$, has received significant support within the fusion community as an attractive fusion reactor blanket material primarily due to its perceived safety advantages over Li. Unfortunately, the neutronic characteristics of this material lead to a large amplification in the neutron leakage through chamber ports. The leakage per DT-neutron is ~ 6 times the solid angle fraction subtended by the ports. As a result, both the tritium breeding ratio and blanket energy deposition decrease at rates much greater than predicted based on the loss of blanket coverage.

In general, the importance of enhanced neutron leakage to reactor design is twofold: first, the shielding requirements along the beam ports may be greater; and second, the calculated reactor performance will be overestimated unless beam ports are included in the neutronics model. The neutron leakage and degradation in blanket performance may be quite significant even if the size of the port is small.

While these calculations were carried out in a geometry representing the beam ports in an ICF chamber, the implications apply to magnetic confinement chambers as well. The enhanced leakage is primarily a

function of the blanket composition and geometry, not the source distribution. Similar trends in neutron leakage and blanket performance can therefore be expected as the result of neutral-beam injection ports and vacuum pumping ports in tokamaks and mirror machines. We anticipate that the mirror reactor, with its injection and pumping at the ends of a long, narrow cylindrical blanket, will be least susceptible to these effects.

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