Nuclear Data for Science and Technology(1988 MITO), 233- 236, Copyright © 1988 JAERI.

NOVEL LOTUS LITHIUM-LEAD FUSION BLANKET CONCEPT

Saber Azam and Anil Kumar[@]

Institut de Génie Atomique, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne,
Switzerland

[@] Present Address : M.A.N.E.D., UCLA, Los Angeles, CA 90024, USA

Abstract : A new lithium-lead blanket is studied on the basis of the following criteria: (i) having a tritium breeding rate of at least 1.1; (ii) having compact modules and (iii) considering the compatibility of structural materials with the primary zonal components. Low-activation ferritic steel is employed as the first wall. This element of the blanket is followed by two breeding zones of $Li_{17}Pb_{83}$ (natural lithium) and Li^6, using respectively the reference vanadium-alloy and the ferritic steel for structural support. Graphite together with the vanadium-alloy fulfils the role of the reflector. A safer variant of the blanket concept, using (SiC) in the reflecting zone, is also studied in spite of its lower albedo with respect to graphite. A flexible experimental module is designed for tritium breeding measurements, foil activation and spectrum measurement purposes.

[Lithium-lead, Blanket concept, Fusion blanket, tritium breeders, Structural materials, Blanket reflectors]

Introduction

The LOTUS experimental facility is originally conceived for integral neutronics measurements in different fusion blanket module configurations:[1] tritium breeding rate (TBR), defined as the total number of tritium atoms produced in the blanket per fusion neutron, neutron spectometry and foil activation.

To now, various measurements have been carried out two types of fusion blanket configurations at the LOTUS facility. The first blanket concept was of fission-suppressed type using Li_2CO_3 and ThO_2 as breeders [2] while the second one was of pure fusion type, employing only Li_2O[3,4]. As a logical continuation of the research activities at the IGA, a new pure fusion blanket concept, for a Tandem Mirror type of fusion reactor (TMR), has been studied based on the recent recommandations established by the leading research institutions[5]. One-dimensional ANISN[6] calculations have been performed for the optimization of different blanket dimensions according to the following criteria:

(a): A TBR of at least 1.1 to guarantee the self-sufficiency of the fusion machine.
(b): A very compact design for the economical and feasibility purposes.
(c): A concept in which the structural material should fully respond, for each zone of the blanket, to the compatibility requirements.

Two leading liquid tritium breeders are used: lithium-metal (enriched in ^6Li) and $Li_{17}Pb_{83}$. Low activation structral materials are considered for each zone on the basis of their compatibility with the blanket components. Graphite forms the main reflector while a safer variant of the blanket, using (SiC) has also been studied. Helium flows through all elements for cooling, particularly the first wall, and reducing tritium contamination, purposes. The total thickness of the proposed design, in either case, is around 47 cm. A flexible experimental module , for the determination of neutronic performance of differnt blanket module configuration, is under construction.

Material Selection

The choice of structural materials, is mainly dictated by the type of tritium breeder(s) used in a fusion blanket. The low-activation ferritic steel (Fe-11Cr-2.5W-0.3V-0.15C) is retained as the first wall due to its resistance to high irradiation doses, its low tritium permeation capacity and its relatively high operating temperature. The reference vanadium-alloy (V-15Cr-5Ti) would be used with the $Li_{17}Pb_{83}$ eutectic due mainly to its high corrosion resistance. The low-activation ferritic steel is selected to be used with the lithium-metal in order to reduce the tritium permeation to the cooling agent. The same vanadium-alloy is used with the graphite or (SiC) reflectors due mainly to its good neutronics properties in generating additional heat by (n,γ) reactions.

Optimization of Blanket Design

One-dimensional optimization calculations were carried out for a TMR type of machine, with P_3-S_8, due mainly to its geometrical and plasma fence simplicities compared to the Tokamak. The calculations were based on the optimization criteria mentioned earlier. DLC-47 [7] and MACKLIB-IV[8] transport and response cross-section libraries were used. It is to be noted that the present 1-D studies for a cylindrical geometry would certainly be optimistic with respect to more realistic 2-D (eventually 3-D) calculations in which the complex neutron source distribution is taken into consideration. However, the general philosophy outlined here would not be affected. Table 1 gives some important information about the blanket-components, studied for the optimization purposes:

Table 1: Blanket Components Composition

Material used	Density [g/cm^3]	Volume Fraction %Structure	%Helium
Ferritic Steel	7.87	-	-
Be	1.62*	8.0	20.0
Li(N)(a)	0.53	5.5	24.5
Li6	0.53	5.5	24.5
Li(N)Pb(b)	9.40	5.5	24.5
Li^6Pb(c)	9.40	5.5	24.5
Graphite	2.26	20.0	15.0
SiC	3.22	20.0	15.0

* 87.6% of the theoritical density (swelling problems)
(a): Natural lithium-metal
(b): $Li_{17}Pb_{83}$ with natural lithium
(c): $Li_{17}Pb_{83}$ entirely enriched in ^6Li

Keeping the total TBR constant and equal to 1.1, several blanket designs have been studied. Each concept consists of a plasma confinement (radius = 50 cm) followed by 10 cm void and the blanket. The first wall and reflector of each blanket are, respectively, constituted of 0.5 cm low-activation ferritic steel and 20.0 cm reference vanadium-alloy. The rest of the blanket configuration and materials have been changed, in each case, in order to cover a large range of possibilities. Table 2 gives a summary of comparative results for five different blanket concepts:

Table 2: Comparison of Five Different Concepts

Elements	Concepts				
	1	2	3	4	5
Plasma	50 cm (D,T)	50 cm (D,T)	50 cm (D,T)	50 cm (D,T)	50 cm (D,T)
Void	10 cm	10 cm	10 cm	10 cm	10 cm
First Wall	0.5 cm FS	0.5 cm FS	0.5 cm FS	0.5 cm FS	0.5 cm FS
Multiplier	-	-	5 cm Be	3 cm Be	-
Breeder-1	90 cm Li(N)Pb	60 cm Li^6Pb	80 cm Li(N)Pb	17 cm Li(N)Pb	18 cm Li(N)Pb
Breeder-2	- -	- -	- -	40 cm Li(N)	45 cm Li(N)
V-alloy Reflector	20 cm	20 cm	20 cm	20 cm	20 cm
Total Diameter	341 cm	281 cm	331 cm	281 cm	287 cm

It could be noticed, from Table 2, that the total diameters of the fusion machine for concept 1 to 5 are respectively 341, 281, 331, 281 and 287 cm. The blankets would, therefore, be very thick. In a cylindrical geometry, big outer dimensions would imply huge volume and weight. One of the objectives of the present study, as was mentioned earlier, is to define a compact design.

The use of beryllium with the Li(N)Pb does not seem to be advantageous contrary to its known and recommended use with the Li^6Pb breeder[9]. Li(N)Pb together with lithium-metal (Concept 5) would also give a rather big blanket. We have also studied the possibility of using only Li^6Pb instead of Li(N)Pb and lithium-metal; but no significant improvement is achieved, and as it is shown in Figure 1 the corresponding blanket would still be very thick.

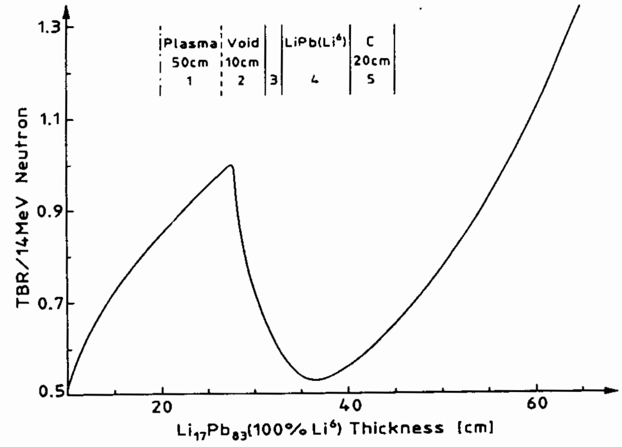

Figure 1: Li^6Pb as a Single Breeder in a Blanket

It is interesting, however, to notice that in this case the TBR increases with Li^6Pb thickness to reach a peak value of 0.99 at thickness of around 27 cm, drops rapidly to a value of 0.53 and then restarts to increase normally. Taking into consideration the above-mentioned results, we have focused our interest on the use of Li(N)Pb together with enriched lithium-metal.

The Optimized Blanket

The first wall was selected to be 0.5 cm. This value corresponds to that of an inherently safe type of blanket[10]. The rest of the calculations were carried out to find the optimum dimensions of a blanket using not more than 20 cm of Li(N)Pb, as this thickness would be sufficient for slowing down the neutrons to near the resonance for $Li^6(n,\alpha)H^3$ reaction, and 10 cm of enriched lithium-metal.

Using Li(N)Pb at the front face of a fusion reactor blanket may have the advantage of producing tritium with the soft neutronic spectrum coming out from the plasma. The soft neutrons would, therefore, be captured immediately to produce tritium by $Li^6(n,\alpha)H^3$ reaction; intermediary neutrons would produce tritium by $Li^7(n,n'\alpha)H^3$ reaction as well and the very hard part of the spectrum provokes the (n,2n) neutron multiplication reaction in lead, leading at the same time to slowing down of the neutron spectrum. 100% Li^6 enrichment was selected for lithium-metal to have reference values for comparison purposes. It has to be mentioned that the results obtained for 90% enrichment are very close to the reference ones.

The optimized blanket would be composed of 0.5 cm low-activation ferritic steel first wall followed by 18 cm Li(N)Pb breeding/multiplying zone, 8.5 cm Li^6 breeding zone and 20 cm graphite reflector. Figure 2 shows schematically how the different elements of the blanket would be situated.

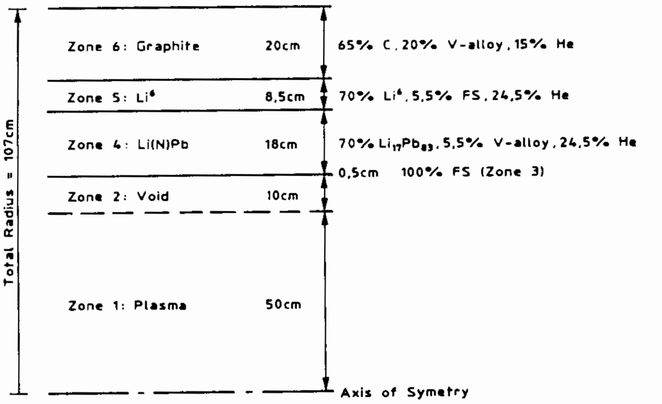

Figure 2: The Optimized Fusion Blanket

This concept of pure fusion blanket would rather be a compact one, having a thickness of 0.47 m. The total TBR, within the two breeding zones of this blanket, is 1.11. Figures 3a, 3b and 3c show respectively the right-boundary neutronic spectrum for the first-wall (zone 3), the Li(N)Pb breeding-multiplying segment (zone 4) and the Li^6 breeding segment (zone 5) of the optimized blanket. As expected the 14 MeV source neutron peak is increasingly submerged by the softer component of the neutron spectrum. Another variant of the optimized blanket, using (SiC) as reflector, has also been studied, owing to the fact that graphite, in spite of being

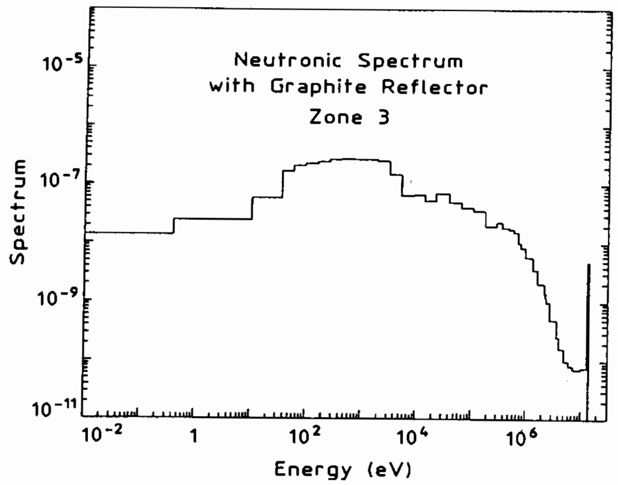

Figure 3a: Neutronic Spectrum (Zone 3)

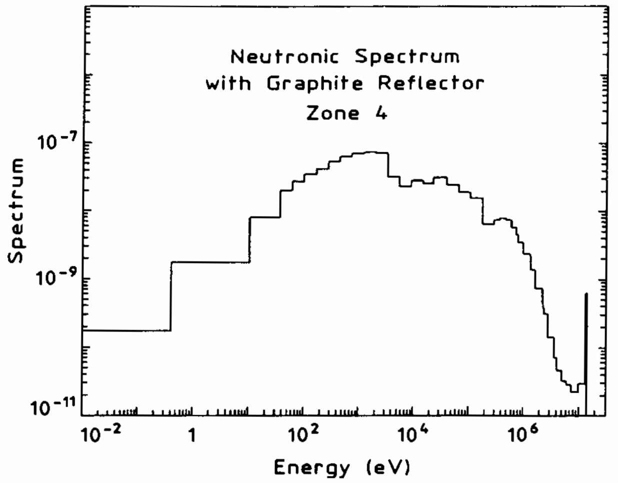

Figure 3b: Neutronic Spectrum (Zone 4)

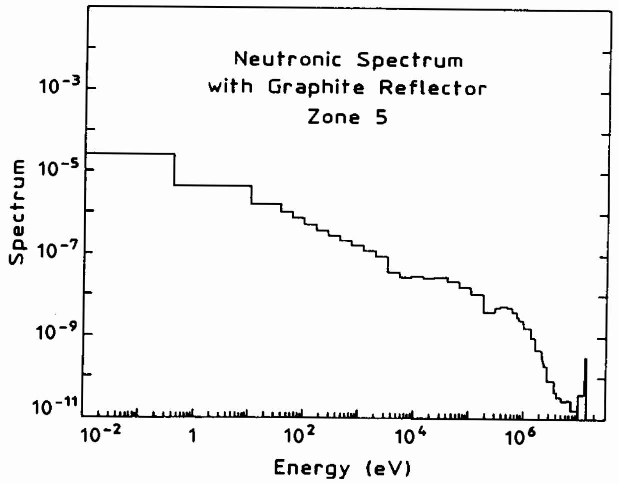

Figure 3c: Neutronic Spectrum (Zone 5)

a good neutron reflector, is chemically less stable than (SiC) and, hence, its use, in a high temperature medium, may represent some danger. This variant is composed of 0.5 cm low-activation ferritic steel first wall, 18 cm Li(N)Pb breeding/multiplying zone, 9 cm Li^6 breeding zone and 19.5 cm (SiC) reflector. This safer variant would be as compact as the selected concept with the graphite reflector. The total TBR would be 1.07, and therefore, is lower than for the optimized concept.

From the engineering point of view, the optimized blanket modules may be similar to those of a Helium-Cooled Liquid-Lithium[11] concept.

Experimental Lithium-Lead Blanket Module (EL^{2}M)

General Considerations

It was mentioned earlier that the Helium-Cooled Liquid-Lithium concept could constitute the basis of engineering design for the optimized blanket. However, owing to the impracticability of placing a large volume - 36 cm diameter and 58 cm long - Haefely 14 MeV neutron generator, used at the LOTUS facility, inside cylindrical blanket, we have had to alter it suitably. The experimental version, called as Experimental Lithium-Lead Module (EL^{2}M), consists of: 1 cm thick SS 304 first wall, 60 cm lithium-lead breeder zone and 20 cm graphite reflector

It was also mentioned earlier that the material choice for the numerical studies is based on the Blanket Comparison and Selection Study[4]. Some of the alloys are, however, not yet available commercially. On the contrary, commercailly available materials are selected for the EL^{2}M. Our limited financial resources and the experimental chamber dimensions (3.6 m x 2.4 m and a height of 3.0 m) are two additional constraining factors that have affected the design of the EL^{2}M.

Mechanical Design

The EL^{2}M is already under construction at the LOTUS facility. The structure of the module consists of three stainless steel (SS 304) bored slabs. Each one, rectified in both sides, has a surface of 100 cm x 100 cm and a thickness of 1 cm. They are maintained at a distance of 40.5 cm from each other. The structure slabs support about 850 stainless steel (SS 304) breeder tubes in which pellets of natural lithium and lead would be placed. Breeder tubes have a lenght of 85 cm and a diameter of 2.8 cm. The choice of the diameter is based on the dimension of our Mini-NE213 and/or Mini-NE230 detectors (external diameter equal to 2.60 cm in both cases). Figure 4 shows an overall view of the experimental blanket module:

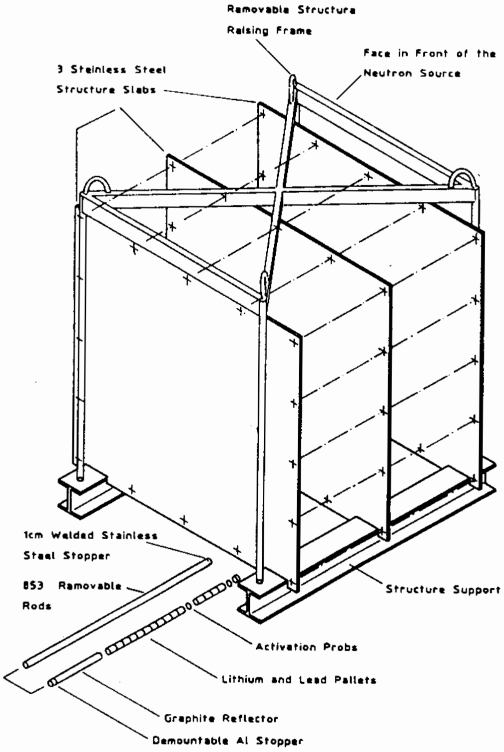

Figure 4: An Overall View of the EL^{2}M

It is planned to measure neutronic spectrum along the blanket module; therefore, the detector has to be placed inside the tubes. Lead pellets have a diameter of 2.78 cm and a length of 2.5 cm; where the dimensions of the lithium pellets are respectively 2.68 and 2.73 cm. Due to their inflammable character, lithium pellets are hermetically protected (laser welding) in thin aluminium containers. Each container has an internal diameter of 2.7 cm, a length of 3.0 cm and a wall-thickness of 0.04 cm. The cover of the container is also of hollow cylindrical form, having respectively dimensions of 2.62, 0.2, and 0.04 cm.

The diameter of the breeder tubes would allow the insertion of the Mini-NE213 and/or Mini NE230 detectors in the module, for spectrum measurement purposes. The container-cover of the lithium pellets would permit suitable welding possiblity. Its external surface could also be used as probe-chamber for the activation measurements. A spring is used in each tube to adjust the breeder length according to the module configuration. Figure 5 represents a section through one tube of the EL^{2}M.

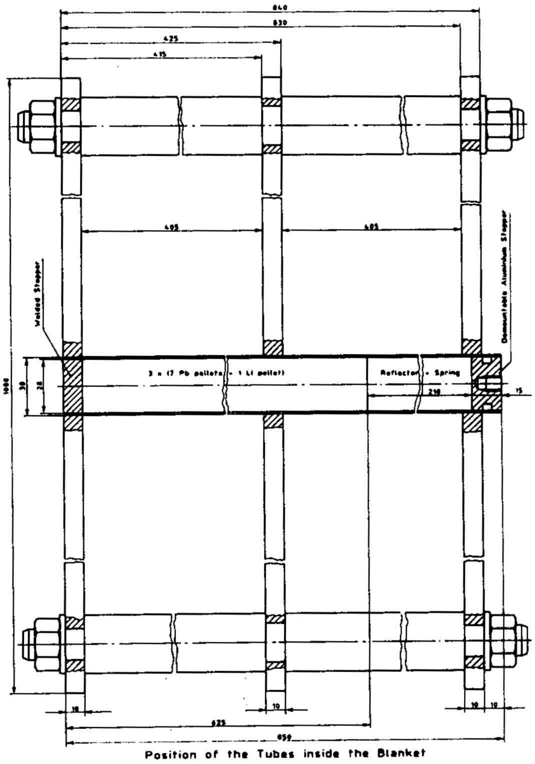

Figure 5: A Section Through one Tube of the EL^{2}M

Using the EL^{2}M, the three main types of blanket module configurations could easily be realised:

(a): Pure Lithium Module: Using entirely lithium - filled tubes in the EL^{2}M. In this case, each breeder tube would be composed of 60 cm natural Li-metal followed by 20 cm graphite reflector.

(b): Li$_{17}$Pb$_{83}$ Module: Using both lithium and lead pellets in the EL^{2}M. The proportion of lithium to lead pellets is 1:7. The breeder tube would, therefore, be composed of 61.5 cm lithium and lead pellets [3 x (1 x 3 cm + 7 x 2.5 cm)], followed by 20 cm graphite reflector.

(c): Li$_7$Pb$_2$ Module: Using lithium and lead pellets in the proportion of 5 lithium to 2 lead. In this case, each breeder tube of the EL^{2}M would be composed of 60 cm lithium and lead pellets [3 x (5 x 3 cm + 2 x 2.5 cm)] followed by 20 cm graphite reflector.

It has to be underlined that other configurations, i.e. lithium lead eutectic and lithium-metal configurations are also very easy to realise with the EL^{2}M.

Planned Experiments

It was pointed out, earlier, that the mechanical design of the EL2M is also based on the possibility of carrying out all planned experiments at the LOTUS facility; i.e.: (i) Foil activation for the determination of different reaction rates, (ii) TBR measurements using conventional techniques and eventually novel techniques[12] and (iii) spectrum measurements employing mini detectors that are much more suitable with respect to the standard NE213 scintillator[13].

Conclusions

A new compact fusion blanket design, using eutectic lithium lead Li$_{17}$Pb$_{83}$ (natural lithium) and enriched lithium-metal is studied with one-dimensional ANISN code together with its safer variant. The total TBR is computed to be 1.11. The experimental module, designed for the measurements of reaction rates, spectrum and total TBR would also allow the realisation of other blanket configurations, i.e. pure Li$_7$Pb$_2$, Li$_{17}$Pb$_{83}$ and lithium-metal for example.

REFERENCES

1. L. Green, "LOTUS Test Sequence and Experimental Methods Development", IGA-LPR LC-GN-04 Internal Report (1983)
2. S.I. Abdul-Khalik, P.-A. Haldy and A. Kumar, "Blanket Design and Calculated Performance for the LOTUS Fusion-Fission Hybrid Test Facility", Nuclear Technology/Fusion, 5, 189 (1984)
3. D.L. Jassby, "Overview of the TFTR Blanket Module Program", Fusion Technology, 10, 925 (1986)
4. J. Quancy, S. Azam and P. Bertone, "Tritium Assay of Li$_2$O in the LBM/LOTUS Experiments", Fusion Technology, 10, 972 (1986)
5. D.L., Smith, Ch.C. Baker, D.K. Sze, G.D. Morgan, M.A. Abdou, S.J. Piet, K.R. Schultz, R.W. Moir and J.D. Gordon, "Overview of the Blanket Comparison and Selection Study", Fusion Technology, 8, 1(1985)
6. W.W. Engle,Jr., "ANISN A One-dimensional Discrete Ordinates Transport Code with Anisotropic Scattering", K-1693, ORNL (1967)
7. R.W. Roussin and C.R. Weisbin, "DLC-47/BUGLE Cross-Section Data", ORNL (1977)
8. Y. Gohar and M.A. Abdou, "MACKLIB-IV A Library of Nuclear Responses Functions Generated with the MACK-IV Computer Program from ENDF/B-V", ANL/FPP/TM-106 (1978)
9. I.N. Sviatoslavsky, M.E. Sawan, L.A. El-Guebaly, L.J. Wittenberg, M.L. Corradini, W.F. Vogelsang and G.L. Kulcinski, "Thin Blanket Design for MINIMARS - A Compact Tandem Mirror Fusion Reactor", Fusion Technology, 10, 609 (1986)
10. J.K. Garner, C.F. Carson, J.D. Gordon and R.H. Whitely, "An Inherently Safe Tandem Mirror Fusion Blanket Concept", Fusion Technology, 10, 615 (1986)
11. C.P. Wong, R.F. Bourque, E.T. Cheng, R.L. Creedon, I. Maya and R.H. Ryder, "Helium-Cooled Blanket Designs", Fusion Technology, 8, 114 (1985)
12. A. Kumar, S. Azam, W.R. Leo, Ch. Sahraoui, P. Strasser, F. Fernandez and J.-P. Schneeberger, "Two Novel Techniques of Tritium Measurement at the Fusion Neutronics Facility LOTUS", to be submitted for publication.
13. V.V. Verbinski , "Calibration of an Organic Scintillator for Neutron Spectrometry", Nuclear Instruments and Methods, 65, 8 (1968)