Turk J Engin Environ Sci
24 (2000) , 373 – 382.

Neutronic Analysis of Flux Dispersion in a Multi-Layered, (D-T) Driven Hybrid Blanket

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Received 26.01.1999

Abstract

The concept of 'hybrid blanket' is based on the placement of the nuclear fuel layer, which is a fertile material and fissionable by the fusion neutrons, at the front or the rear sides of the tritium breeding zone so that, in addition to gaining fission energy, a fissile fuel is produced. The neutronic flux distribution (neutron spectrum) along the radial direction varies with the type of material and the geometry used in the blanket, and also according to whether it is multi-layered or single-layered. The flatness of neutron flux is important for the flatness of power production.

In this study, a cylindrical hybrid blanket with a mixture fuel (UO_2+CmO_2), C reflector, and LiO_2 tritium breeding material is neutronically analyzed. While the hybrid blanket is analyzed by separating it into 79 intervals, the neutronic flux distribution in the fuel and other layers are calculated by transforming the reflector and the tritium breeding zones to one-, two-, and three-layered structures respectively according to their volumes. The multi-layered structure and the partial moderation both lead to neutron economy and smoother flux distribution. Therefore, it can be concluded that the multi-layered blanket structure is advantageous for a flat power output. The flux functions of the fuel and other zones are calculated by using the transport code ANISN-ORNL and the data libraries DLC-36 and SINEX. The results are presented graphically as a function of the radius of the reactor, and compared with each other.

Key Words: Hybrid Blanket, Fission, Fusion, Multi-Layer Blanket, Fissile and Fusile Breeding

Çok Katmanlı, (D-T) Sürücülü Bir Hibrid Blanketteki Akı Dağılımının Nötronik Analizi

Özet

Hibrid Blanket (örtü) anlayışı, füzyon blanketinde, trityum üretim katmanının önüne ve arkasına füzyon nötronları ile bölünebilen (fertil) bir nükleer yakıt katmanının konması ve bu şekilde, bölünme enerjisi ile birlikte, termal (yavaş) nötronlarla parçalanabilen (fisil) yakıt üretiminin de gerçekleşmesi esasına dayanır. Böyle bir blanket içerisinde yer alan malzemeye ve blanketin geometrisine bağlı olarak, radyal doğrultu boyunca nötronik akı dağılımı, blanketin katmanlı veya katmansız olmasına bağlı olarak değişim göstermektedir. Bu değişiminin, mümkün mertebe düzgün olması, güç üretiminin düzgünlüğü açısından önemlidir.

Bu çalışmada, (UO_2+CmO_2) karışık yakıtlı, C yansıtıcılı ve LiO_2 trityum üretim malzemeli, silindirik hibrid blanket, nötronik analize tabi tutulmuştur. Hibrid blanket 79 aralığa bölünerek incelenirken, trityum ve yansıtıcı katmanları sırasıyla, sabit hacimde, tek, iki ve üç katmanlı hale getirilerek, yakıt ve diğer katmanlardaki akı dağılımı hesaplanmıştır. Katmanlı yapı ile sağlanan nötron ekonomisi ve nötron hızındaki kısmi azalma (moderasyon) nedeniyle, daha düzgün bir akı dağılımı elde edilmiştir. Bu ise, düzgün bir güç çıktısı için, katmanlı blanket yapısının avantajlı olabileceğini ifade etmektedir. Katmanlı yapıdaki, yakıt ve diğer bölgelerin akı fonksiyonları, ANIS-ORNL transport kodu, DLC-36 ve SINEX data paketleri kullanılarak hesaplanmıştır. Hesaplama ile elde edilen sonuçlar, grafiklerle verilmiş ve sonuçlar karşılaştırılmıştır.

Anahtar Sözcükler: Hibrid Blanket, Fisyon, Füzyon, Çok Katmanlı Blanket, Fisil ve Fusil Üretim

1. Introduction

If the energy consumption rate increases at 2% until the end of this century, it is claimed that the fissile fuel sources that are necessary for the thermal reactors will be insufficient or completely consumed unless other alternative sources are found (Pease, 1992; Greenspan et al., 1981; Mior, 1981). Fast-breeding reactors (FBRs) play an important role in supplying fissile fuels with their 10 to 30 doubling time. In addition to energy production, FBRs produce their own fuel. The fuel production can be improved by feeding the reactor with external neutrons. Fusion power is assumed to be a very important potential at this point (Kulcinki et al., 1992; Pease, 1992). A new reactor technology that will aim to benefit from fusion energy involves fission and fusion together, and is currently an important area of research. The basic idea in this system, called a hybrid reactor, is to surround the fusion plasma resulting from (D-T) or D-D reactions by a layer of a fuel that can be changed into fissile fuel (Youssef et al., 1979; Leonard, 1973; Yatahama et al., 1994). Thus, this system is largely based on the fusion reactors. With this system, while one part of the fuel in the fertile fuel layer helps the energy production, the remaining part is used for the production of the fissile fuel that can be used in thermal reactors. The amount of the fissile fuel produced in this system might be approximately 30 times more than the fuel that is produced in the fast reactors, and the energy obtained might be 20-40 times greater than the energy of the individually operated fusion reactors. Hybrid reactors have a higher security factor than other reactors because the hybrid blanket always operates under sub-critical conditions. This system has a great advantage over fission reactors since it makes use of thermal reactor waste, which is radioactive as well. It involves two different systems, fusion and fission, and requires the solution of the operation problems related to these systems concurrently, and thus has a complex structure despite its advantages. Reactions such as (D-T), (D-D) or (D-^{3}He) are the sources of the fusion neutron. The (D-T) fusion reaction, which is shown with equation (1), is the most current of these reactions and partly commercial.

$$D + T \rightarrow \alpha + n + 17.6(\text{MeV}) \quad (1)$$

The neutron on the right-hand side of equation (1) carries a high amount of energy, 14.1 MeV. Neutrons having this much energy can be used as FBRs. In this case, the environment in which the fusion reactions take place in hybrid reactors is called fusion drivers. The main purpose in these drivers is to maintain the fusion plasma at a certain geometry without touching the first wall surrounding itself. The drivers are classified into three groups: the Tokamak, Tandem mirror, and Inertia types. The most important of these drivers in practice is the Tokamak type (Lawrence, 1976; Şahin et al., 1976).

The general structure of a hybrid reactor is such that the first wall surrounds the fusion driver, and fertile or fissile fuel blankets are behind the first wall. The function of the first wall is to protect the neighboring blankets from thermal and electromagnetic radiation. Therefore, the material of the first wall is required to have the ability tocarry out this duty (Enrich, 1977). The function of the advanced hybrid blanket is, if the fusion reaction is at (D-T) mode, to accomplish both the fissile and fusile fuel productions. Thus, a hybrid system is expected to produce more fuel than it consumes.

In the (D-T) reaction, although the amount of the D fusile fuel component is sufficienty, the T (tritium) component needs to be produced since it is an artificial element. The fissile fuel breeding results from the fertile-fissile conversion with (n, γ) reaction in the fertile blanket, and tritium breeding (fusile breeding) takes place in the tritium breeding zone (TBZ), which is positioned behind the fuel layer and contains Li_2O. The following reactions show how the transformation takes place. T, which is the by-product of the reactions of equation (2) and equation (3), is back-supplied to the (D-T) environment as a fuel by an appropriate method.

$$^6Li + n \rightarrow \alpha + T + 4.748(\text{MeV}) \quad (2)$$

$$^7Li + n \rightarrow \alpha + T - 2.422(\text{MeV}) \quad (3)$$

The production of fissile fuel from the fertile fuel in the fuel zone of the blanket results from the following fission reaction:

$$\text{Fertile Fuel } + n \rightarrow \text{ Fissile Fuel } + \nu n' + 200(\text{MeV}) \quad (4)$$

The neutron, which is on the left-hand side of equation (4) (i.e., n) and starts the reaction, is a fast neutron, and the source of this neutron is the (D-T) fusion reaction. The neutron on the right-hand side of equation (4) (i.e., n') is a relatively thermalized one, and contributes to the continuation of the thermal fission reactions and the nuclear energy production (Abdul, 1984; Abdoul, 1982). For generating the necessary transformations, both the energy and the neutron number have to be increased at a rate greater than 1.

Studies on the geometric structures of hybrid reactors show that the cylindrical structure has the highest performance of all the geometries (Harker et al., 1984; Şahin et al., 1983; Al-Kusayer et al., 1983a, 1983b; Şahin et al., 1986). In addition to the geometric structure, the other criterion is the distribution of the power. To have a constant power distribution for a reactor is a desired and important feature. While obtaining a constant power distribution curve (Erikson et al., 1981; Greenspan et al., 1983), an optimum fuel operation in a hybrid blanket producing plutonium has been reached. Tritium production and reflector zones positioned behind the fuel layer with constant density have been transformed to the multilayered state and the power distribution has been analyzed (Şahin et al., 1986; Greenspan et al., 1983; Şahin, 1980; Şahin, 1981; Şahin et al., 1982; Şahin, 1983; Şahin et al., 1984; Şahin et al., 1986). The density in the fuel zone and the volume in every part of the reactor were kept constant for that purpose. Tritium production and reflector zones, which were placed after the fuel layer containing (UO_2+CmO_2), are transformed into two and three layers in such a way that these layers are interconnected (sandwich).

The power distribution of a hybrid reactor can be calculated from the following equation (Duderstad et al., 1976):

$$P = E_N \int \int \nu(E)\Sigma(r,E)\Phi(r,E)dEdV \quad (5)$$

As seen from equation (5), the most important parameter in the determination of the power is the neutron spectrum $\phi(r,E)$. The most important reactions for the reactor environment are fission reactions (n, f).

2. Description of the Blanket

Figure 1 shows the geometric structure of the investigated blanket. As seen from the blanket geometry, the calculations involve line fusion neutron source (F) (Şahin, et al., 1986). Hybrid blanket consists of four main components as seen in Fig. 1:

- The cylindrical first wall has a thickness of 1.3 cm and is made of stainless steel type 316. This one corresponds to the first wall of the Tokamak Fusion Test Reactor (TFTR) at Princeton University.

- Ten rows of fuel rods made of mixture fuel (UO_2 +CmO_2) make up the fuel zone. Each fuel rod with a diameter of 10 mm was cladded with an aluminum hollow cylinder (D_0 = 12 mm, D_i = 10.4 mm). The fuel zone is arranged hexagonally with this fuel rod. In addition, to simulate a gas-cooled blanket, a volume fraction of 42% for air is permitted in this structure.

- The tritium breeding zone, made of Li_2O, has a thickness of 21 cm, which is used to breed tritium (T) for (D,T) fusion reaction.

- The reflector layer made of graphite (C) has a thickness of 26 cm, which is used to decrease neutron leakage.

Table 1 gives the material structure of the appropriate layers and the densities of the nucleus. The radius of the fuel, tritium breeding and reflector zones in cylindrical geometry were taken from the geometric structure that was proposed with the Ayman project.

The change in the flux and energy curves of the new geometric structures obtained by increasing the number of the tritium and reflector layers to two or three layers respectively without affecting the volume of the fuel zone will be analyzed. It is very important to keep the volume of the reactor constant while increasing the number of layers. The dimensioning of the new two-and three-layered structures were obtained by keeping the volumes of the tritium breeding zone and the reflector zone constant while equation (6) and equation (7) were also kept constant. The new geometric structures, which were obtained by increasing the number of tritium and reflector layers in the blanket geometry of Fig. 1, are shown in Fig. 2.

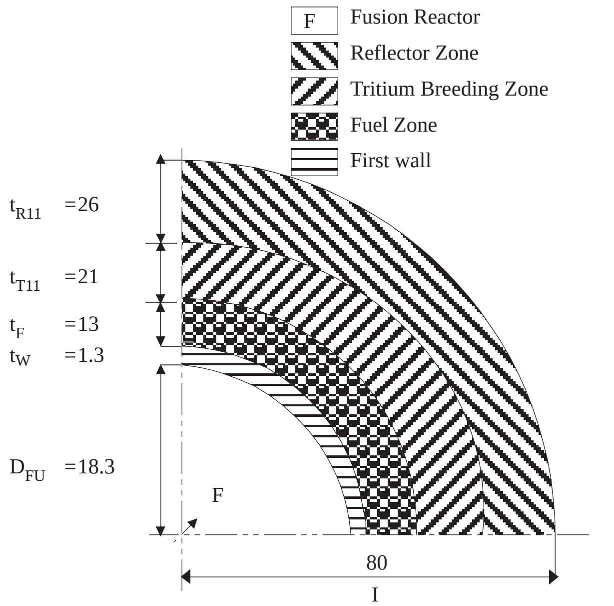

Figure 1. Cross-Sectional view of the investigated hybrid blanket (Dimensions in cm)

$$D_{Tnm} = (((D_{FU} + t_w + t_F + t_{T11})^2 + (n-m)(D_{FU} + t_w + t_F)^2 + (m-1)^2)/n)^{1/2} \quad (6)$$

$$D_{Rnm} = ((m(D_{FU} + t_w + t_F + t_{T11} + t_{R11})^2 + (n-m)(D_{FU} + t_w + t_F)^2)/n)^{1/2} \quad (7)$$

Where n, m are the number of layers and the layer number respectively.

3. Numerical Calculations

The analysis of the neutron populations at different points of the hybrid blanket will be useful in interpreting the obtained results. The flux distribution of the environment describes the neutron spectrum of the same environment, and, moreover, the neutron spectrum has very important characteristics for explaining the neutronic events at different points of the blanket. The variation in the neutron spectrum is analyzed for the fuel zone consisting of ten rows of (UO_2+CmO_2). The materials of the tritium breeding and reflector zones are Li_2O and graphite respectively. The calculations of the neutron spectrum are performed by separating the blanket into intervals.

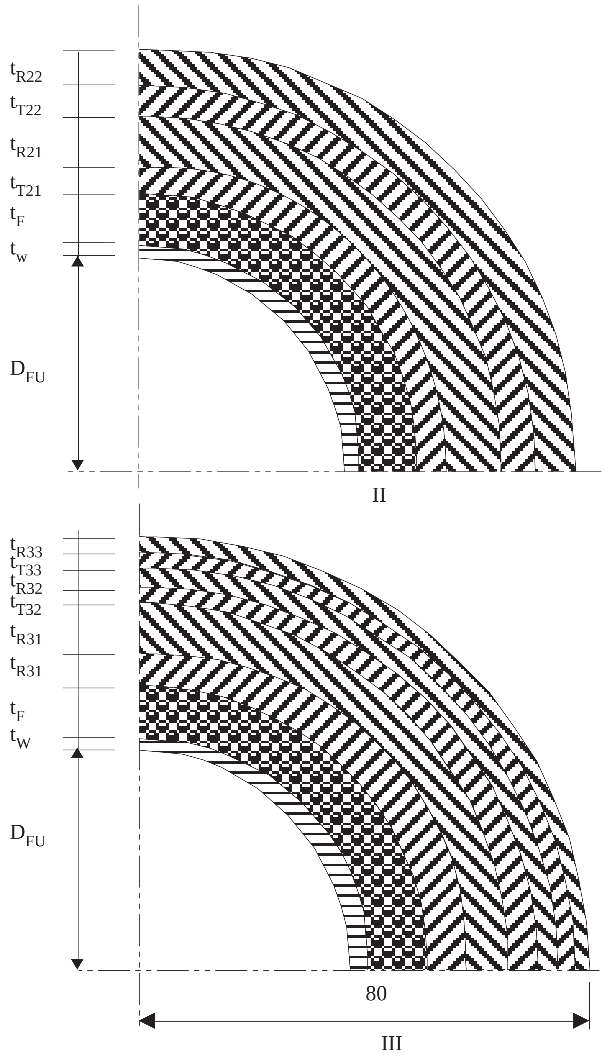

Figure 2. Cross-Sectional view of the multi-layer structure hybrid blanket (Dimensions in cm). II. two-layer structure, and III. three-layer structure obtained by maintaining the volumes of the tritium and reflector zone.

The blanket geometry consists of 79 intervals that are layered as shown in Fig. 2 provided that the volume is constant. The neutron spectra in the fuel zone of the multi-layered blanket geometry are calculated for the first interval (adjacent to the first wall), for the center interval of the fuel zone, and for the last interval (adjacent to the first tritium breeding zone) of both situations, two-layered and three-layered.

Table 1. Material composition of the investigated blanket

Zone	Material	Nuclide	Nuclide Density ($10^{30}/m^3$)		
First Wall	Type 316 stainless Steel	Silicon	1.7108-3[a]		
		Chromium	1.6627-2		
		Manganese	1.7548-3		
		Iron	5.75651-2		
		Nickel	8.1863-3		
		Molybdenum	1.0022-3		
Cladding	AlO_2	Oxygen	1.5763-2		
		Aluminum	8.6791-3		
Fuel	UO_2+CmO_2	Row of the Fuel Rods	U^{235}	U^{238}	Cm^{244}
		1	5.627-5	7.825-3	0.0
		2	5.502-5	7.651-3	1.750-4
		3	5.380-5	7.478-3	3.499-4
		4	5.253-5	7.304-3	5.249-4
		5	5.128-5	7.130-3	6.999-4
		6	5.003-5	6.957-3	8.748-4
		7	4.878-5	6.783-3	1.050-3
		8	4.753-5	6.609-3	1.225-3
		9	4.628-5	6.435-3	1.400-3
		10	4.502-5	6.260-3	1.576-3
Tritium Breeding	Li_2O	Li-6	4.6379-3		
		Li-7	5.7038-2		
		Oxygen	3.083-2		
		Aluminum	3.0136-3		
Reflector	Graphite	Carbon	1.1284-1		

a- Read as 1.7108×10^{-3}

The spatial variation of the average neutron energy throughout the investigated hybrid blankets for different layer structures is shown in Fig. 3. For a better comprehension of the shift in the neuron spectrum it is useful to investigate the average neutron energy in the blanket, defined as

$$E^* = (\int E\Phi(E)dE)/(\int \Phi(E)dE) \qquad (8)$$

and plotted in Fig. 3. There is a continuous decrease in the neutron energy by deeper penetration with some small oscillations by passing from the graphite zones into the Li_2O zones, where the average neutron energy shows a small increase due to strong absorption at lower energies. The rate of decrease in the average neutron energy gets smaller as the number of layers increases.

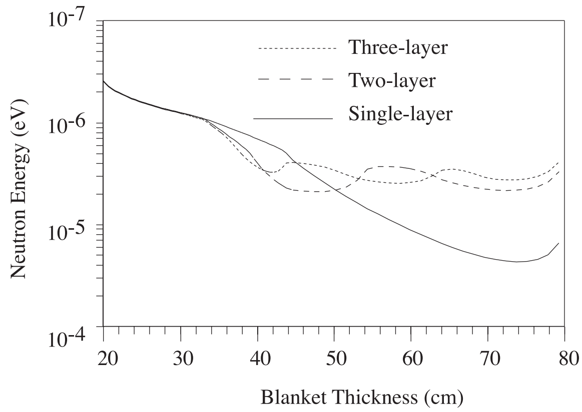

Figure 3. Average Neutron Energy per (D-T) neutron in the investigated blankets (see Fig. 1 and Fig. 2)

The shift in the neutron spectrum throughout the blanket can be understood by observing the average neutron energy (see eq. 8), which is a function of the radial dimension of the blanket, and the neutron flux and energy at different points in the blanket. Neutron spectrum curves (fluxes) drawn for each midpoint of the blanket zones are given in Figs. 4-7 as a function of energy. In accordance with the foregoing remarks, the neutron spectrum curves show a variation towards the outer boundary, from harder neutron spectrum shapes to softer ones. Figure 4 shows the neutron spectrum at the selected point (first, center and last intervals) in the fuel zone. In this figure, the curves related to the first interval of the fuel zone (adjacent to the first wall) show that there is a softening in the neutron spectrum without any fluctuation. This behavior can be explained by the decrease of the number of high-energy neutrons, and the increase in the number of low-energy neutrons. At the same time, it can be stated that the first wall, though it is thin, can moderate the fusion neutrons with 14.1 MeV. The neutron density in the first interval changes in favor of low energy neutrons since their number increases as a result of the fission reactions caused by 14.1 MeV fusion neutrons. The neutron spectrum in the fuel zone shows fast softening as it approaches the center interval. This behavior can be explained by the moderation of neutrons. When the number of layers is increased from one to two and more, the softening rate decreases, as seen Figs. 4 and 5. It is noted that, in all blankets, there is a decrease in flux in the energy interval of 2-75 eV, and the center interval of the fuel zone has the sharpest decrease. In all intervals, the decrease in the single-layer structure is more than that in the multi-layered structure. It can be concluded that the multi-layer structure flattens the neutron spectrum to some extent. This decrease must be due to the absorption of neutrons by the fuel. In all blankets, the flux values in the high-energy region within the range of $3 \times 10^3 - 2 \times 10^4$ eV are the same. When the first maximum value of the flux values of the blankets is considered, the flux values in the high energy region show four-fold softening as we go from a single-layer structure to a two-layer structure. However, the softening rate increases up to twenty-twofold for the change from single-layer structure to a three-layer structure. The softening increases as much as five times for the change from a two-layer structure to three-layer structure. As the number of layers in a multi-layer structure increases, the neutron spectrum keeps softening and the neutron spectrum curve approaches to more stable and steady curve.

Figure 5 shows the neutron spectrum at the selected points (first and last intervals) in the reflector. In this figure, the neutron spectrum in the immediate vicinity of the first tritium breeding zone (TBZ) decreases by deeper penetration into the reflector zone. Again, as seen in Fig. 5, the rate of decrease in the neutron flux increases as the number of blanket layers increases. The rate of the decrease in the neutron flux related to only the outer interval of the reflector zone is plotted against average neutron energy in Fig. 6.

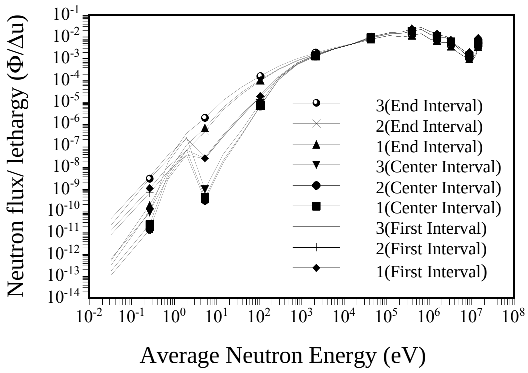

Figure 4. Variation of the neutron spectrum throughout the fuel zone. 1. Single-layer, 2. Two-layer, 3. Three-layer

Figure 7 depicts the neutron spectrum at a selected point in TBZ. The neutron transport calculations for the cylindrical geometry were performed by the computer code ANISN-ORNL (Engle, 1964; Al-Kusayer et al., 1988) and with $S_{18} - P_3$ approximation.

The neutronic performance parameters of the investigated blanket in Table 2 are defined as follows:

$$M = \text{(Fission Heat + Heat Release in } {}^6Li)/14.1 + 1 \quad (9)$$

$$k^*_{eff} = ((\int\int \nu\Sigma_f \Phi dVdE)/(\int\int \Sigma_a \Phi dVdE + \int\int JdSdE) \quad (10)$$

$$k^{**}_{eff} = \int\int (\nu\Sigma_f + 2x\sigma_{2n})\Phi dVdE/(\int\int (\Sigma_a + \Sigma_{2n})\Phi dVdE + \int\int JdSdE) \quad (11)$$

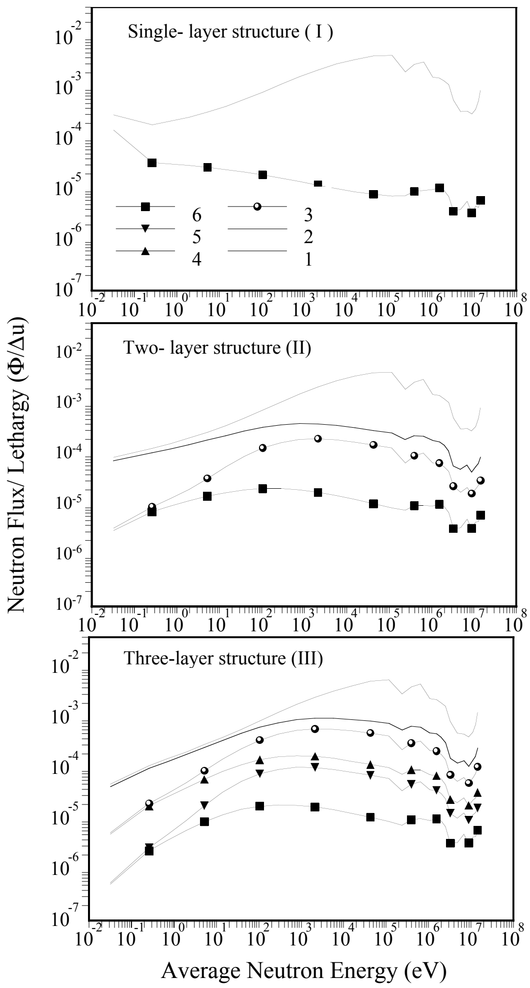

Figure 5. Variation of the neutron spectrum in the reflector zone, 1. adjacent to first TBZ, 2. in the back of the first reflector zone , 3. adjacent to second TBZ, 4. in the back of the second reflector zone, 5. adjacent to the third TBZ, 6. outer interval of the reflector zone

where M and k_{eff} are the energy multiplication factor and the neutron multiplication factor respectively. An increase in the number of tritium and reflector layers from single-layer (see Fig. 1 (I)) to two-layer (see Fig. 2 (II)) increases total fissile breeding (n, γ) by a factor of 1.079, total fusile breeding by a factor of 1.0753, total breeding by factor of 1.076, M by a factor of 1.013, and k^*_{eff} by a factor of 1.007, and decreases the neutron leakage by a factor of 1.92. As above, an increase in the number of tritium and reflector layers from single-layer to three-layer (see Fig. 2 (III)) increases total fissile breeding (n, γ) by a factor of 1.408, total fusile breeding by a factor of 1.062, total breeding by factor of 1.135, M by a factor of 1.023, and k^*_{eff} by a factor of 1.018, and decreases the neutron leakage by a factor of 2.17.

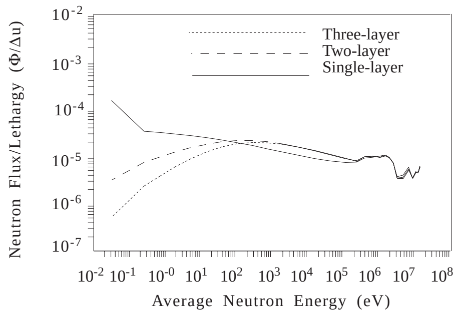

Figure 6. Variation of the neutron spectrum in the outer interval of the reflector zone

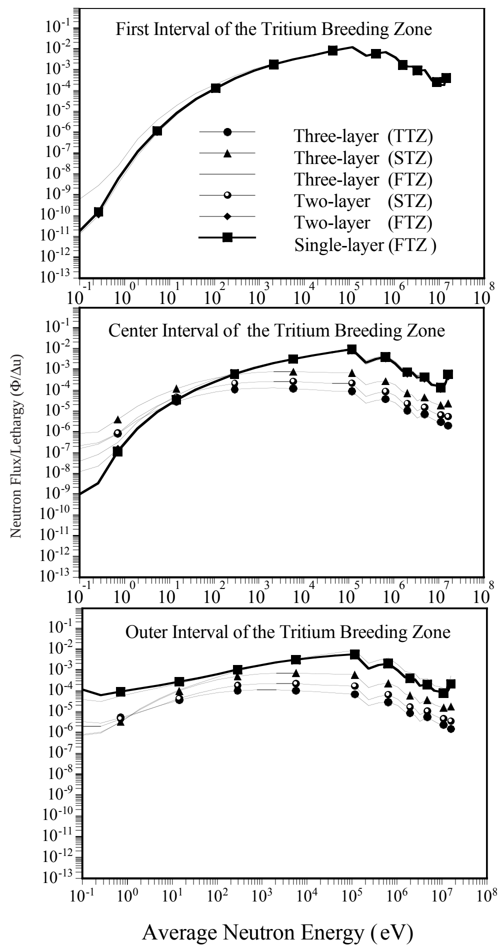

Figure 7. Variation of the neutron spectrum in the tritium breeding zone (TBZ), first tritium zone (FTZ), second tritium zone (STZ), third tritium zone (TTZ))

Table 2. Neutronic Performance of the Investigated Hybrid Blanket Using Multi-layer Blanket Structures (Values per D-T neutron)

	One Layer			Two Layers			Three Layers		
	Fuel Components								
	Blanket type[a]: I			II			III		
	U^{235}	U^{238}	Cm^{244}	U^{235}	U^{238}	Cm^{244}	U^{235}	U^{238}	Cm^{244}
$Li^6(n,\alpha)T$	(Equation (2))		1.181	1.2921			1.290		
$Li^7(n,\alpha T$	(Equation (3))		0.1024	0.0878			0.026		
Total T	1.2834			1.380			1.363		
$(n,2n)$	1.347-4	4.688-2	5.374-4	1.348-4	3.191-1	5.377-4	1.349-4	4.695-2	5.382-4
(n,γ)	0.0	2.970-1	4.593-2	0.0	3.191-1	5.085-2	0.0	3.549-1	5.870-2
(n,f)	1.506-2	1.796-1	1.076-1	1.559-2	1.802-1	1.089-1	1.639-2	1.815-1	1.115-1
$^c(n,2n)$	4.755-2[b]			3.197-1			4.763-2		
$^c(n,\gamma)$	3.429-1			3.699-1			4.828-1		
$^c(n,f)$	3.0208-1			3.0466-1			3.088-1		
[d]	1.626			1.750			1.846		
M	5.686			5.760			5.818		
k^*_{eff}	0.553			0.557			0.563		
k^{**}_{eff}	0.583			0.763			0.592		
Leakage	0.228			0.119			0.105		
Absorp.	2.011			2.1400			2.1862		

a. Structure of the Blanket (see Fig. 1 and Fig. 2)
I. Cavity Radius (D_{FU}) 18.7cm+1.3 cm SS+13 cm (UO_2+CmO_2) (fuel)+21cm LiO_2+26 cm C
II. Cavity Radius (D_{FU}) 18.7 cm+1.3 cm SS+ 13 cm (UO_2+CmO_2) (fuel)+11.75cm LiO_2+16.44 cm C+7.06 cm LiO_2 +11.75 cm C
III. Cavity Radius (D_{FU}) 18.7 cm+1.3 cm SS+ 13 cm (UO_2+CmO_2) (fuel)+8.21cm LiO_2+12.26 cm C+5.42 cm LiO_2 +9.75 cm C+3.74 cm LiO_2 +7.62 cm C
b. Read as 4.755×10^{-2}
c. Total
d. Total Breeding(T6+T7+(n,γ))
$*$ defined, in (equation (9)) including $(n,2n)$ reaction
$**$ defined, in (equation (10)) excluding $(n,2n)$ reaction

4. Conclusions

The neutronic performance of the hybrid blanket for multi-layer blanket structure has been analyzed in this study. The main conclusions are as follows:

1. Utilization of fusion neutrons in a hybrid system indicates the necessity for the reconsideration of the opinions of the people who think that thermonuclear reactor technology is not commercially viable for the near future. It also plays an effective role in maintaining thermal reactors.

2. The analysis of the neutron spectrum curves resulting at different points in a blanket can be considered to yield valuable criteria as it provides information about the neutronic behavior of the blanket.

3. It can also be stated that the transformation of the tritium breeding and reflector zones to the multi-layered structures at a constant volume significant in obtaining the smooth flux distribution. Since smoothness in flux distribution results in smoothness at the power output, the improvements in the fuel zone can be evaluated together with the multi-layering process.

Nomenclature

E	:	Energy
J	:	Neutron Current
k_{eff}	:	Effective Neutron Multiplication Coefficient Of The Hybrid Blanket
M	:	Blanket Energy Multiplication Factor
dS	:	Differential Surface Element
dV	:	Differential Volume Element
D	:	Blanket Diameter

Subscripts

a	:	Absorption
b	:	Breeding
f	:	Fission
N	:	Nucleus
2n	:	(n,2n)
F	:	Fuel
T	:	Tritium
R	:	Reflector
W	:	First Wall

Greek Letters

γ	:	Capture Cross Section
ν	:	Neutron Production Per Fission
Σ	:	Macroscopic Cross Section
Φ	:	Neutron Flux
σ	:	Microscopic Cross Section

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