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NEUTRONIC OPTIMIZATION OF SOLID BREEDER BLANKETS FOR STARFIRE DESIGN*

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Summary

Extensive neutronic tradeoff studies were carried out to define and optimize the neutronic performance of the different solid breeder options for the STARFIRE blanket design. A set of criteria were employed to select the potential blanket materials. The basic criteria include the neutronic performance, tritium-release characteristics, material compatibility, and chemical stability. Three blanket options were analyzed. The first option is based on separate zones for each basic blanket function where the neutron multiplier is kept in a separate zone. The second option is a heterogeneous blanket type with two tritium breeder zones. In the first zone the tritium breeder is assembled in a neutron multiplier matrix behind the first wall while the second zone has a neutron moderator matrix instead of the neutron multiplier. The third blanket option is similar to the second concept except the tritium breeder and the neutron multiplier form a homogeneous mixture.

The analyses were carried out for different tritium breeders, neutron multipliers, and coolants. Four lithium compounds, $LiAlO_2$, Li_2SiO_3, Li_2O, and Li_7Pb_2, representing the potential candidates from the ceramic and intermetallic compounds; three coolant materials, H_2O, D_2O, and helium; and six neutron multipliers, Be, BeO, Pb, PbO, Zr, and Zr_5Pb_3, are used in the parametric and optimization studies.

The ^6Li enrichment and blanket dimensions are defined from a one-dimensional cylindrical model. The final analysis of the STARFIRE reference design is based on three-dimensional Monte Carlo calculations that account for the rf and and limiter system, the spacial distribution of plasma neutron source, and the thickness restriction on the inner blanket.

Introduction

The basic functions of a fusion reactor blanket are to maximize the blanket energy deposition per fusion neutron, to breed sufficient tritium, and to provide some protection for the toroidal field magnets within the imposed constraints on the blanket thickness. These requirements were used to define and optimize a blanket for STARFIRE design focusing on the use of solid lithium compounds for tritium breeding. The neutronic performance of candidate neutron multipliers, tritium breeders, and coolants are analyzed. The impact of the tritium breeder and neutron multiplier arrangement, and ^6Li enrichment on the blanket performance are presented. Finally, the neutronic performance of the reference blanket design based on one- and three-dimensional neutronic models is analyzed.

Blanket Geometry Options

The solid breeder blanket concept with continous tritium recovery by means of a helium purge stream has been utilized for the STARFIRE design. Unfortunately, the existence of the other elements with the lithium isotopes in the solid breeder material and the high percentage of the structural material result in a tritium breeding ratio of less than one. Consequently, the fusion neutron interactions with these elements reduce the tritium generation from the ^7Li isotope. Furthermore, the parasitic neutron interactions with these elements result in less capture in the ^6Li isotope for tritium generation. The remedy to this problem is to include a neutron multiplier to produce more neutrons through (n,2n) and (n,3n) interactions.[1-5]

There are some exceptional solid breeder materials with high lithium content which can produce a tritium breeding ratio greater than one without a neutron multiplier. These solid breeders are Li_2O and LiH. The use of these materials results in design problems, e.g., large tritium inventory for Li_2O, low melting point for LiH and other safety problems.

The nonfissionable neutron multiplier can be incorporated with the solid breeder in three different blanket options. In the first option, the neutron multiplier is placed in a separate zone in front of the breeding zone. The second option is a heterogeneous blanket type with two tritium breeder zones. In the first zone the tritium breeder is assembled in a neutron multiplier

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matrix behind the first wall while the second zone has a neutron moderator matrix instead of the neutron multiplier. The third blanket option is similar to the second option except the tritium breeder and the neutron multiplier form a homogeneous mixture. The second breeder zone in the last two blanket options may contain a solid breeder only to simplify the design.

In the first option, where the fusion neutrons must pass through the neutron multiplier before reaching the solid breeder, the resulting neutron flux entering the solid breeder is much softer than the first wall neutron flux. However, the neutron flux into the tritium breeding zone is increased. The softer spectrum, which results from the interactions with the neutron multiplier, reduces the probability of neutron interactions with ^{7}Li to produce tritium from the $^{7}Li(n;n',\alpha)T$ reaction. The result is to depend on ^{6}Li to produce most of the tritium from the $^{6}Li(n,\alpha)T$ interaction.

The separate zones option has more flexibility to adjust the average operating temperature for each zone independently. The operating temperature of the solid breeder can be adjusted to match the temperature range suggested for the optimum operating conditions as defined by the tritium extraction process. The main drawback in this option is that all the neutrons have to pass through the neutron multiplier and the second wall before reaching the solid breeder zone. This transport process reduces the number of neutrons avialable for interaction with the solid breeder due to the parasitic neutron interactions in the second wall and the neutron multiplier zone.

In the second blanket option, the resulting tritium breeding ratio and the energy deposition per fusion neutron are higher than the corresponding values from the separate zones blanket option. The primary reason for the improved performance is that the neutrons travel less distance to reach the solid breeder, and hence, the parasitic absorption is reduced. However, the design of this option is more difficult, and since it requires more structural material, it is less desirable from the radwaste point of view.

The third option is also intended to further improve the nuclear performance of the blanket and simplify the mechanical design. Where the homogeneous medium may contain two compounds mixed together (for example, BeO + $LiAlO_2$) or one compound which has lithium and neutron multiplier atoms (for example, Li_2ZrO_3). As anticipated, the nuclear performance can be improved for a particular materials system and the mechanical design is relatively simple. However, this concept is limited to only a few neutron multiplier and breeding material combinations because of compatibility considerations.

Neutronic Analysis of the Neutron Multipliers

The nuclear data for nonfissionable material were examined to identify elements with (n,2n) or (n,3n) cross sections in the energy range up to 14.1 MeV. Table 1 gives a list of the potential candidates along with some relevant parameters for each candidate. The neutron multiplication cross section is relatively high and it is of the order of 1 to 3 barn per atom for the heavy materials at 14 MeV neutron energy. For lighter materials, the (n,2n) cross sections are typically lower except for beryllium and deuterium. The (n,2n) cross sections for the light materials remain relatively high down to lower threshold energies compared to the heavy materials. The other important neutronic considerations are the absorption cross sections, e.g., $\sigma(n,\gamma) + \sigma(n,\gamma) + \sigma(n,D) + \sigma(n,\alpha) \ldots$, and the inelastic cross sections. These cross sections should be small to qualify the material as a good neutron multiplier from the neutronic point of view. Analysis of the elements with significant (n,2n) and (n, 3n) cross sections indicates that Pb, Bi, Be, and Zr have the highest potential for neutron multiplication among the candidates listed. Beryllium has been used as a neutron multiplier for several reactor studies,[1,2] and lead has also been suggested[3-5] because it has low absorption cross sections.

In order to compare the performance of the different neutron multipliers, a one-dimensional neutronic analysis was performed to determine the tritium breeding capability, the heat deposition per fusion neutron, and the radioactive isotopes with long half-lives generated from the multiplier materials. The analyses were carried out for two different blanket concepts. In both sets of calculations $LiAlO_2$ (α-phase) solid breeder with 90% ^{6}Li enrichment, PCA structure, and H_2O coolant are used with different neutron multipliers. The separate zones blanket option described in the previous section is employed for these analyses. The differences between the two concepts are related to the neutron multiplier zone design. In the first concept the neutron multiplier is internally cooled by water tubes embedded inside the neutron multiplier material (internally cooled neutron multiplier) while the second concept uses the first wall and second wall water coolant to remove the heat from the neutron multiplier material (externally cooled neutron multiplier). The zone volumetric compositions for the two blanket concepts are given in Table 2.

The tritium breeding ratio and the energy deposition per fusion neutron for the internally cooled multiplier concept are plotted in Figs. 1 and 2, respectively, as a function of the neutron multiplier thickness. Vanadium, niobium, molybdenum, and tungsten neutron multipliers were excluded because of insufficient tritium breeding capability and other considerations

Table 1. Properties of Candidate Neutron Multiplier Materials

Material:	Be	BeO	Pb	PbO	Bi	Zr	Zr_5Pb_3	PbBi
Density, g/cm^3	1.85	2.96	11.34	9.53	9.8	7.6	8.93	10.46
Atoms or molecules/cm^3 $\times 10^{-24}$	0.1236	0.07127	0.03348	0.02571	0.02824	0.04291	0.004680	0.03047
$\sigma(n,2n)$ at 14 MeV, barns	0.5	0.5	2.2	2.2	2.2	0.6	9.2	2.2
$\Sigma(n,2n)$ at 14 MeV, cm^{-1}	0.0618	0.0256	0.0737	0.0565	0.0621	0.0257	0.0431	0.0670
Threshold energy for (n,2n) cross section, MeV	1.868	1.868	6.765	6.765	7.442	7.274	6.765	6.765
$\sigma(n,\gamma)$ at 0.0253 eV, barns	0.0095	0.0095	0.17	0.17	0.034	0.18	0.141	0.095
$\Sigma(n,\gamma)$ at 0.0253 eV, cm^{-1}	0.001174	0.0006711	0.005692	0.004369	0.0009602	0.006599	0.002905	0.3534
Radioactivity								
Isotopes	^{10}Be	^{10}Be	^{205}Pb	^{205}Pb	^{210}Po	^{93}Zr	^{93}Zr, ^{205}Pb	^{205}Pb ^{210}Po
Decay types	B^-	B^-	Ec	Ec	α, γ	B^-	B^-, Ec	Ec, α, γ
Half lives,	1.6×10^6 y	1.6×10^6 y	3.0×10^7 y	3.0×10^7 y	138.4 d	1.5×10^6 y	1.5×10^6 y 3×10^7 y	3×10^7 y 138.1 d
Melting point, °C	1278	2520	327.5	888	271.3	1852	1400	125
Thermal conductivity[a] at 25°C, W/m-°K	201	216[b]	35.3	2.8	7.92[c]	22.7	——	2.3[d]

[a]At 25°C.

[b]Pure beryllium oxide, hot pressed.

[c]Polycrystalline.

[d]At 200°C.

Table 2. Blanket Parameters for Internally Cooled and Externally Cooled Neutron Multiplier Concepts

Zone Description	Zone Thickness (cm)	Zone Composition, vol-%: Externally Cooled	Zone Composition, vol-%: Internally Cooled
First wall	1	50% PCA 50% H_2O	50% PCA 50% H_2O
Neutron multiplier	Variable	100% neutron multiplier	85% neutron multiplier 10% PCA 5% H_2O
Second wall[a]	1	25% PCA 25% H_2O	No second wall
Tritium breeder	50	80% $LiAlO_2$[b] 10% PCA 5% H_2O 5% He purge	80% $LiAlO_2$[b] 10% PCA 5% H_2O 5% He purge
Reflector	15	50% carbon 25% PCA 25% H_2O	50% carbon 25% PCA 25% H_2O

[a]Second wall is 50% by volume void.
[b]90% ^6Li.

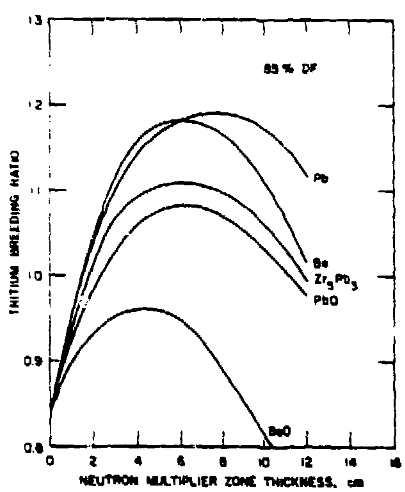


Fig. 1. Tritium breeding ratio from the separate zones blanket option for different neutron multipliers (internally cooled) with $LiAlO_2$ (90% ^6Li) breeder, H_2O coolant, and PCA structure.

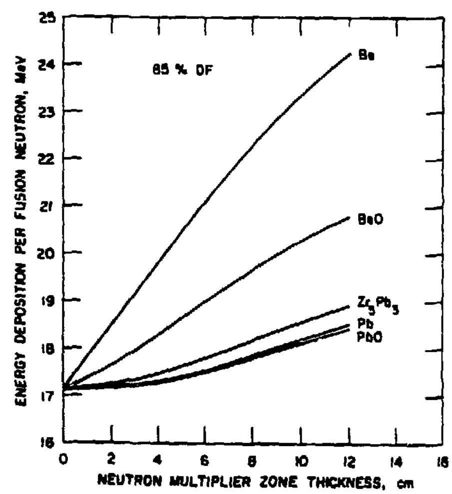


Fig. 2. Nuclear energy deposition per fusion neutron from the separate zones blanket option for the different neutron multipliers (internally cooled) for $LiAlO_2$ (90% ^6Li) breeder, H_2O coolant, and PCA structure.

Table 3. Blanket Neutronic Parameters at the Maximum Tritium Breeding Ratio from the Separate Zones Blanket Option for Different Neutron Multipliers (Internally Cooled) with $LiAlO_2$ (90% ^6Li) Breeder, H_2O Coolant, PCA Structure

Neutron Multiplier Material	Pb	Be	Zr_5Pb_3	PbO	BeO
Tritium breeding ratio	1.19	1.18	1.11	1.08	0.96
Multiplier zone thickness (cm)	7.5	6	6	6	4
Energy per fusion neutron (MeV)	17.8	21.1	17.8	17.5	18.3
(n,2n) reactions from the neutron multiplier per fusion neutron	0.42	0.61	0.31	0.28	0.24
(n,γ) reactions from the PCA structure per fusion neutron	0.22	0.34	0.14	0.16	0.13

(for example, tungsten for fabrication problems, vanadium for compatibilty problems with water coolant, niobium and molybdenum for long-term activation problems). The beryllium and lead neutron multipliers exhibit the highest tritium breeding ratio in this blanket concept because of its large (n,2n) cross section at the 14-MeV neutron energy and because of its very low capture cross section. The beryllium neutron multiplier produces more neutrons per fusion neutron compared to the other neutron multipliers; however, the maximum breeding ratio is about the same as that for lead (see Table 3). This is due primarily to the softer spectrum from beryllium and the high slowing-down power of the H_2O coolant which results in more parasitic neutron interactions in the structural material per fusion neutron as shown in Table 3. The unique feature of the beryllium multiplier is the high energy deposition per fusion neutron that is desirable from the economic point of view. The Zr_5Pb_3 and PbO neutron multipliers show a maximum tritium breeding ratio of 1.11 and 1.08, respectively, which is probably insufficient for a practical system. The tritium breeding capability from this blanket concept can be improved by using heavy water which has a lower slowing-down power instead of ordinary water.

The second concept, in which the neutron multiplier material is cooled externally from both sides (first wall and second wall), provides for a simpler blanket mechanical design and improves the blanket nuclear performance. The tritium breeding ratios and the energy deposition per fusion neutron are plotted in Figs. 3 and 4, respectively, as a function of the neutron multiplier zone thickness. The beryllium neutron multiplier shows the highest tritium breeding ratio in this blanket concept because the neutron slowing down by the water coolant and the parasitic reactions in the structural material in the neutron multiplier zone are eliminated. Table 4 shows the (n,2n) reactions from the neutron multiplier and the (n,γ) reactions from the PCA structure per fusion neutron at a breeding ratio of 1.2 or the maximum tritium breeding ratio attainable if less than 1.2.

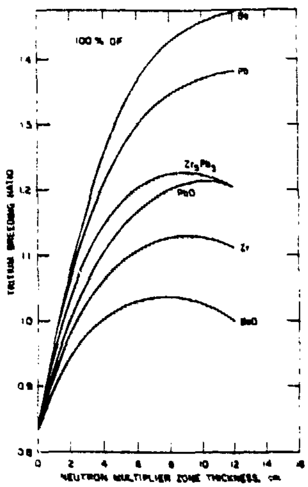
It is clear from Tables 3 and 4 that the performance of the beryllium neutron multiplier is improved in the second blanket concept. The lead neutron multiplier also shows an improvement, and the Zr_3Pb_3 and PbO neutron multipliers provide a breeding ratio greater than 1.2 in the second concept. Since Pb, Bi, and PbBi neutron multipliers are quite similar from the neutronic point of view, the neutronic calculations are carried out for lead only.

From the previous results, it appears that Be, Pb, PbBi, Bi, Zr_5Pb_3, and PbO are the potential candidates as neutron multipliers from the neutronic point of view. The choice among these multipliers depends on the physical properties, design criteria, and other considerations (cost, resources, radwaste, etc.). The ratioactive isotopes with long half-lives from the different neutron multipliers are given in Table 1.

Neutronic Analysis of the Tritium Breeding Materials

The neutronic analyses were carried out for four lithium compounds: $LiAlO_2$ (α-phase), Li_2SiO_3, Li_2O, and Li_7Pb_2, representing the potential candidates from the ceramic and intermetallic compounds. The $LiAlO_2$ and Li_2SiO_3 breeder have similar neutronic performance, both need a neutron multiplier to achieve a tritium breeding ratio greater than one. Li_7Pb_2 represents the homogeneous blanket option where the tritium breeding element (lithium) exists as a compound with the neutron multiplier element (lead). Li_2O is one of the few solid breeders that has the potential for tritium breeding without a neutron multiplier.

The separate zones blanket option described before with a Zr_5Pb_3 neutron multiplier, PCA structure, and H_2O coolant is used for the neutronic analysis of $LiAlO_2$ tritium breeding



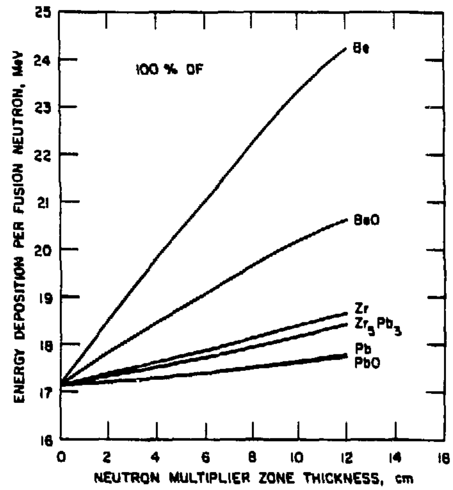


Fig. 3. Tritium breeding ratio from the separate zones blanket option for different neutron multipliers (externally cooled) with $LiAlO_2$ (90% ^6Li) breeder, H_2O coolant, and PCA structure.

Fig. 4. Nuclear energy deposition per fusion neutron from the separate zones blanket option for the different neutron multipliers (externally cooled) with $LiAlO_2$ (90% ^6Li) breeder, H_2O coolant, and PCA structure.

Table 4. Blanket Neutronic Parameters at 1.2 or the Maximum Tritium Breeding Ratio from the Separate Zones Blanket Option for Different Neutron Multipliers (externally cooled) with $LiAlO_2$ (90% ^6Li) Breeder, H_2O Coolant, and PCA Structure

Neutron Multiplier Material	Be	Pb	Zr_5Pb_3	Zr	PbO	BeO
Tritium breeding ratio	1.2	1.2	1.2	1.13	1.2	1.04
Multiplier zone thickness (cm)	3.3	3.8	5.9	9	8	8
Energy per fusion neutron (MeV)	19.4	17.2	17.7	18.3	17.5	19.7
(n,2n) reactions from the neutron multiplier per fusion neutron	0.46	0.43	0.34	0.30	0.40	0.47
(n,γ) reactions from the PCA structure per fusion neutron	0.14	0.11	0.10	0.11	0.14	0.29

material. The neutron multiplier material is cooled from the first and second wall to improve the neutronic performance and simplify the mechanical design as discussed before. In this analysis, the impact of ^{6}Li enrichment and the neutron multiplier zone thickness on the blanket performance are examined. In addition, the tritium breeding zone thickness and ^{6}Li burnup are considered in the analysis. The blanket parameters are the same as given in Table 2 for externally cooled neutron multiplier, except a 7-cm thick neutron multiplier and a 50-cm thick reflector (90% C, 5% PCA, and 5% H_2O) are used. The breeding zone thickness and the ^{6}Li enrichment are variable in this analysis.

The tritium breeding ratio contours as a function of the ^{6}Li enrichment and the neutron multiplier zone thickness are given in Fig. 5. The results shown in Fig. 5 indicate that a specific tritium breeding ratio can be achieved with different combination of ^{6}Li enrichment and neutron multiplier zone thickness. In the range of interest for the STARFIRE design, a tritium breeding ratio of 1.2 is achievable with at least three different designs. The first design with a minimum ^{6}Li enrichment of 28% requires an 8-cm neutron multiplier zone thickness. The second design with a minimum neutorn multiplier zone thickness needs at least a 50% ^{6}Li enrichment. The third case, which is characterized by a thicker neutron multiplier and a higher ^{6}Li enrichment, utilizes a 21-cm neutron multiplier zone thickness and a 75% ^{6}Li enrichment. The differences in the maximum heating rate for these blankets are within 5% as shown in Fig. 6. The maximum lithium burnup contours after six years of operation (16.2 MW-yr/m^2) as a function of the ^{6}Li enrichment and the neutron multiplier zone thicknesses are given in Fig. 7.

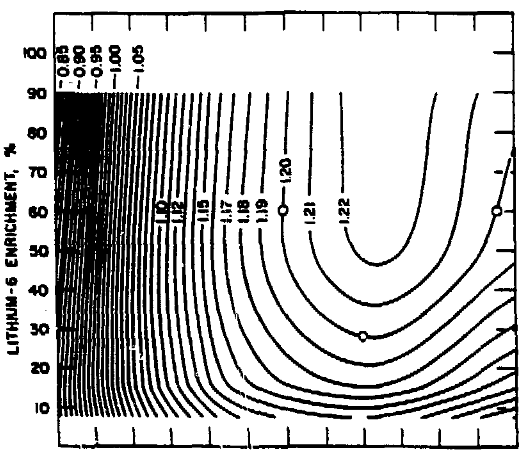


Fig. 5. Tritium breeding ratio contours from the separate zones blanket option with $LiAlO_2$ breeder, Zr_5Pb_3 neutron multiplier, H_2O coolant, and PCA structure.

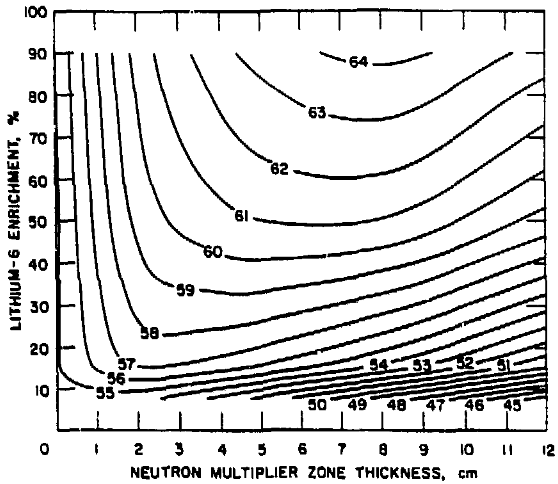


Fig. 6. Maximum heating rate (W/cm^3 contours is the breeder material from the separate zones blanket option with $LiAlO_2$ breeder, Zr_5Pb_3 neutron multiplier, H_2O coolant, and PCA structure.

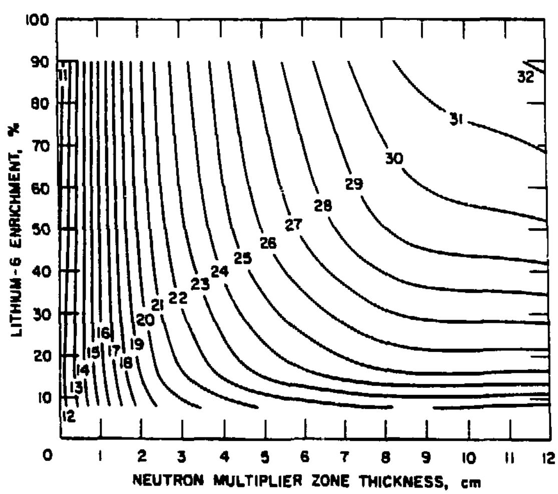


Fig. 7. Maximum lithium burnup (%) contours after six years of operation (16.2 MW-yr/m^2) for the separate zones blanket option with $LiAlO_2$ breeder, Zr_5Pb_3 neutron multiplier, H_2O coolant, and PCA structure.

The maximum lithium burnup increases with both the neutron multiplier zone thickness and the ^{6}Li enrichment because of an increase in the ^{6}Li reaction rate. The difference in the maximum burnup between the blanket with minimum ^{6}Li

enrichment and the corresponding one with minimum neutron multiplier zone thickness for a tritium breeding ratio of 1.2 is less than 1% after six years of operation. However, the blanket with a minimum neutron multiplier zone thickness has the lowest maximum temperature in the neutron multiplier zone which is an important design issue in the blanket design. The blanket with the thick neutron multiplier zone and a high ^6Li enrichment has the lowest energy leakage, while the blanket with minimum ^6Li enrichment has an economic advantage derived from the saving in the ^6Li enrichment cots. In the STARFIRE design, the blanket with minimum neutron multiplier zone thickness is employed because it minimizes the beryllium resource requirement and satisfied the maximum temperature criterion for Zr_5Pb_3 with the external multiplier coolant concept.

The Li_2SiO_3 breeder will generate about ~0.4% more tritium and deposit ~1% less energy per fusion neutron compared to the $LiAlO_2$. However, the main difference between the $LiAlO_2$ and Li_2SiO_3 compounds relates to the radioactivity. Li_2SiO_3 compound does not generate long term radioactive isotopes while $LiAlO_2$ produces ^{26}Al isotope with half-life of 7.3×10^5 yr.

The Li_2O breeding material is a unique candidate because of its potential to breed enough tritium without a neutron multiplier material. Elimination of the neutron multiplier results in much simpler blanket design.

Helium coolant potentially matches the high temperature capability of Li_2O and eliminates the reaction problems associated with water coolant in the tritium breeding zone. Helium coolant occupies large volume fraction of the tritium breeding zone and requires a large amount of structural material which impacts the blanket nuclear performance and increases the blanket thickness. In order to analyze this blanket option, the tritium breeding ratio per fusion neutron as a function of the helium coolant and ferritic steel volume fraction are given in Fig. 8. The blanket parameters used in the calculation are listed in Table 5. A design similar to STARFIRE would be expected to use 30 to 40% helium and 14 to 16% ferritic steel which would result in ~1.2 tritium breeding ratio and ~17.7 MeV energy deposition per fusion neutron.

The lithium lead (Li_7Pb_2) provides a high tritium breeding ratio because of the neutron multiplication from lead. The presence of lithium and lead atoms in a homogeneous compound represents a favorable situation for utilizing the secondary neutrons as discussed before. This situation results in a small blanket thickness to get the required tritium breeding and the nuclear energy. Table 6 lists the blanket parameters used for Li_7Pb_2 neutronic analysis. The water-cooled volume fraction is 20% to keep the maximum temperature in the tritium breeding material below the melting point. An increase in ^6Li enrichment for this

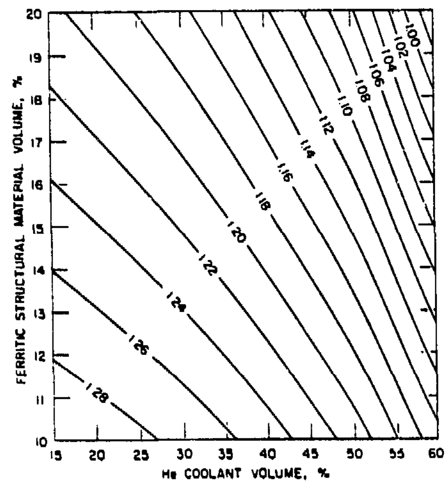


Fig. 8. Tritium breeding ratio contours for Li_2O breeder, He coolant, ferritic steel structure and D_2O first wall coolant.

blanket results in lower values for the tritium breeding ratio and the nuclear heat deposition as shown in Table 7. This blanket requires a 24-cm tritium breeding zone thickness and a 5-cm reflector xone thickness to achieve a tritium breeding ratio of 1.2. This small blanket thickness provides an economic advantage.

Table 5. Blanket Parameters for Different Tritium Breeding Zone Compositions with Li_2O (Natural Lithium) Tritium Breeding Material, Helium Coolant, Ferritic Steel Structure, and D_2O First-Wall Coolant

Zone Description	Zone Thickness (cm)	Zone Composition Percentage by Volume
First wall	1	50% ferritic steel structure
		50% D_2O coolant
Tritium breeding zone	100	(100-X-Y)% Li_2O breeder
		X% ferritic steel structure
		Y% He coolant
Reflector	30	85% C reflector
		5% ferritic steel structure
		10% He coolant

Table 6. Blanket Parameters for Li_7Pb_2 Tritium Breeding Material with H_2O Coolant and Ferritic Steel Structure

Zone Description	Zone Thickness (cm)	Zone Composition Percentage by Volume
First wall	1	50% ferritic steel structure
		50% H_2O coolant
Tritium breeding zone	30	70% Li_7Pb_2 tritium breeder
		10% ferritic steel structure
		20% H_2O coolant
Reflector	5	95% H_2O reflector
		5% ferritic steel structure

Table 7. Tritium Breeding Ratio and Energy Deposition per Fusion Neutron as a Function of the ^6Li Enrichment for Li_7Pb_2 Tritium Breeding Material with H_2O Coolant and Ferritic Steel Structure

^6Li Enrichment (%)	Tritium Breeding Ratio	Energy Deposition per Fusion Neutron (MeV)
7.5 (nat.)	1.344	18.14
15	1.327	17.92
30	1.304	17.77
45	1.280	17.71
90	1.205	17.64

Neutronic Analysis of D_2O Versus H_2O-Cooled Blanket

In order to compare the blanket performance with both H_2O and D_2O, a neutronic analysis for both coolants using the same blanket is given in this section. The blanket employs the lead neutron multiplier in the separate zones blanket option with Li_2SiO_3 (90% ^6Li) tritium breeding material. The blanket parameters are given in Table 8. The resulting tritium breeding ratio from this blanket as a function of the neutron multiplier zone thickness is given in Fig. 9 for both coolants. The D_2O-cooled blanket gives a maximum tritium breeding ratio of 1.43 compared to 1.23 from the H_2O-cooled blanket for neutron multiplier zone thicknesses of 13 and 7.5 cm for D_2O and H_2O, respectively. This difference in the tritium breeding capability is caused primarily by the difference in the slowing-down power of D_2O and H_2O. Figure 10 shows that the neutron multiplication from Pb(n,2n) reactions for both coolants are the same, whereas the neutron capture in the ferritic

Table 8. Blanket Parameters for Separate Zones Blanket Option with D_2O and H_2O Coolant Lead Neutron Multiplier Material, Li_2SiO_3 (90% ^6Li) Tritium Breeding Material, and Ferritic Steel Structure

Zone Description	Zone Thickness (cm)	Zone Composition Percentage by Volume
First wall	1	50% ferritic steel structure
		50% water coolant
Neutron multiplier	Variable	85% Pb neutron multiplier
		10% ferritic steel structure
		5% water coolant
Tritium breeder	50	80% Li_2SiO_3 tritium breeder
		10% ferritic steel structure
		5% water coolant
		5% He purge stream
Reflector	20	90% C reflector
		5% ferritic steel structure
		5% water coolant

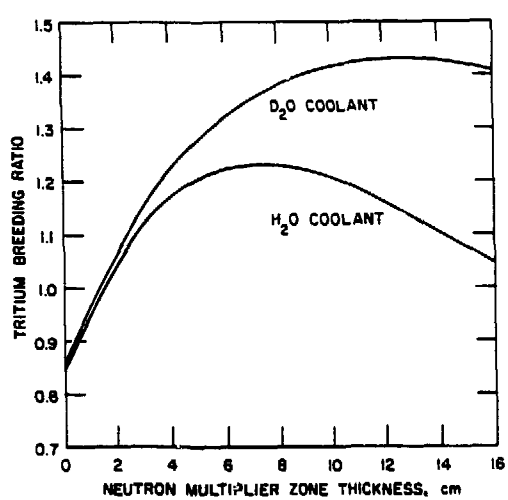


Fig. 9. Tritium breeding ratio from separate zones blanket option with D_2O and H_2O coolant, lead neutron multiplier, Li_2SiO_3 (90% ^6Li) breeder, and ferritic steel structure.

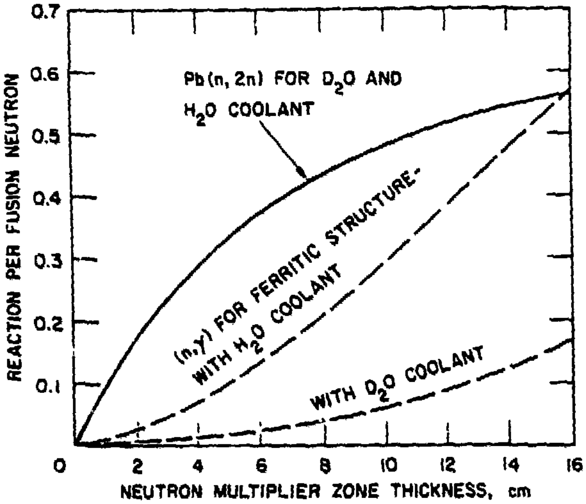


Fig. 10. Pb(n,2n) neutron interaction and (n,γ) capture in the ferritic structure for D_2O and H_2O-cooled blanket with Li_2SiO_3 (90% ^6Li) breeder.

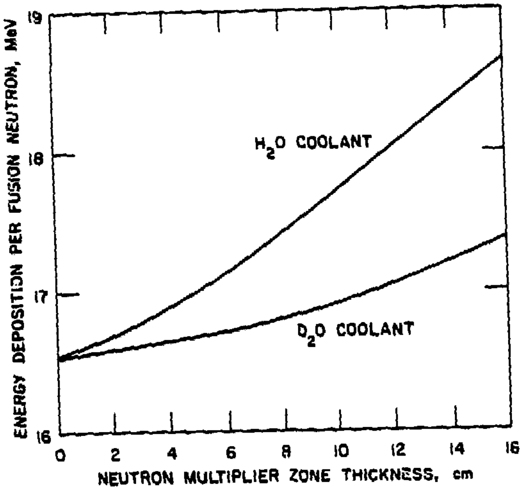


Fig. 11. Nuclear energy deposition per fusion neutron from separate zones blanket option with D_2O and H_2O coolant, lead neutron multiplier, Li_2SiO_3 (90% ^6Li) breeding and ferritic steel structure.

steel structural material is much higher in the H_2O blanket compared to the D_2O blanket. The H_2O coolant moderates the secondary neutrons in the multiplier zone enough to significantly increase the probability for the neutron capture in the ferritic steel structure. More than 95% of the total neutron capture occurs in the first wall and the neutron multiplier structural material. The D_2O coolant does not moderate the neutrons as effectively so that more secondary neutrons proceed into the tritium breeding zone. This also explains the increase in the tritium breeding capability for the blanket with externally cooled neutron multipliers as discussed before.

The energy per fusion neutron for both coolants is given in Fig. 11 as a function of the neutron multiplier zone thickness. The H_2O-cooled blanket deposits more energy per fusion neutron. This is due to the increase in the neutron capture in the ferritic structure where the Q value for Fe(n,γ) is 7.8 MeV compared to 4.79 MeV for $^6Li(n,\alpha)T$ interaction.

The strong slowing-down power of H_2O increases the maximum burnup in the blanket compared to D_2O-cooled blankets. Figure 12 gives the maximum burnup for both coolants as a function of the neutron multiplier zone thickness. For a tritium breeding ratio of 1.2, the maximum burnup for H_2O-cooled blankets is ~22% at 16.2 MW-yr/m^2 exposure (STARFIRE neutron wall loading integrated over the blanket life) compared to ~10% for D_2O. This higher maximum burnup will also cause a greater change in the blanket temperature distribution at end of life.

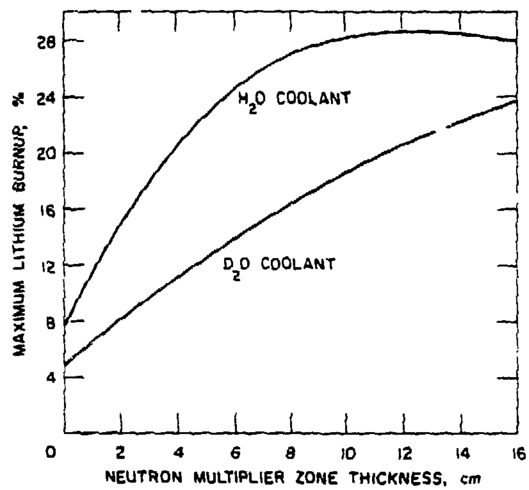


Fig. 12. Maximum lithium burnup at 16.2 MW-yr/m^2 as a function of the neutron multiplier zone thickness for separate zones blanket option with D_2O and H_2O coolant, lead neutron multiplier, Li_2SiO_3 (90% ^6Li) breeder, and ferritic steel structure.

Neutronic Analysis of the STARFIRE Blanket Reference Design

The STARFIRE blanket reference design has evolved from the numerous parametric and trade-off studies. The separate zones blanket concept with two neutron multiplier options, namely, Zr_5Pb_3 and beryllium; $LiAlO_2$ tritium breeder, carbon reflector, and PCA structure are selected for the STARFIRE design. The thickness of each zone is defined based on a one-dimensional analysis. The nuclear performance of the reference design is based on three-dimensional analysis for the entire reactor.

In order to determine the tritium breeding zone thickness, blankets with a variable tritium breeding zone thickness and a 50-cm carbon reflector are analyzed. The blanket parameters are given in Table 9. The resulting tritium breeding ratio and the nuclear energy deposition per fusion neutron are given in Fig. 13. The tritium breeding ratio reaches saturation at ~40-cm tritium breeding zone thickness with more than 99% of the saturation value achieved at a 30-cm thickness. On the other hand, the nuclear energy deposition per fusion neutron decreases with the increase in the tritium breeding zone thickness because of the difference in the Q value of lithium and iron reactions. Therefore, a 30-cm tritium breeding zone thickness is selected for the STARFIRE reference design.

The ^6Li enrichment is based on the neutronic analysis presented before. A 60% ^6Li enrichment is used with the Zr_5Pb_3 neutron multiplier whereas natural lithium is used with the beryllium neutron multiplier.

The use of the neutron multiplier and water coolant, which produces a soft neutron spectrum at the back of the tritium breeding zone, reduces the importance of the reflector. Therefore, a 15-cm reflector is proposed. The analysis shows that the change from a 30 to a 15-cm reflector zone thickness results in only a 0.3% reduction in the tritium breeding ratio and a 0.5% reduction in the nuclear energy deposition per fusion neutron. The fact that the inlet and outlet coolant headers serve as a reflector material increases the effect of the reflector in the STARFIRE design.

The thermal-hydraulic and stress analyses for the reference design indicate a need for less steel in the second wall and less water in the first and second walls than was used in the neutronic analyses. The implementation of of these changes in the first and second wall thicknesses results in less multiplier zone thickness for the same neutronic performance. Decreasing the neutron multiplier zone thickness is desirable because the maximum temperature of the multiplier is reduced for the same neutron wall loading.

Table 9. Blanket Parameters for Analysis of Breeding Zone Thickness with Zr_5Pb_3 Neutron Multiplier, $LiAlO_2$ (60% ^6Li) Tritium Breeding Material, PCA Structure, and H_2O Coolant

Zone Description	Zone Thickness (cm)	Zone Composition Percentage by Volume
First wall	1	50% PCA steel structure
		50% H_2O coolant
Neutron multiplier	7	100% Zr_5Pb_3 neutron multiplier material
Second wall	1	50% PCA steel structure
		25% H_2O coolant
Tritium breeder	Variable	80% $LiAlO_2$ tritium breeder
		10% PCA steel structure
		5% H_2O coolant 5% He purge stream
Reflector	50	90% C reflector
		5% PCA steel structure
		5% H_2O coolant

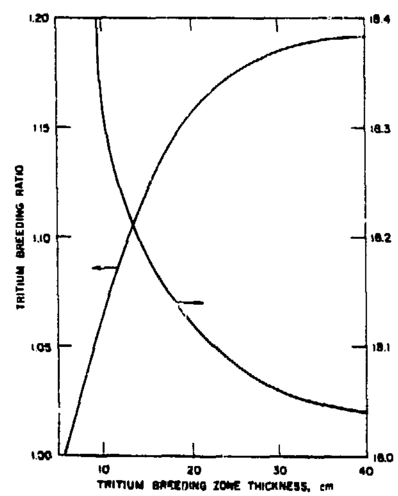


Fig. 13. Tritium breeding ratio and energy deposition per fusion neutron as a function of the breeding zone thickness with Zr_5Pb_3 neutron multiplier, $LiAlO_2$ (60% ^6Li), PCA structure, and H_2O coolant.

The STARFIRE blanket reference parameters are given in Table 10. The same blanket parameters are used for beryllium neutron multiplier except a natural lithium and a 0.7 density factor for the multiplier zone are imposed on the parameters in Table 10. The density factor for the beryllium neutron multiplier will accommodate any swelling. The tritium breeding material also has a 0.6 density factor to enhance the tritium release characteristics. Therefore, the 30-cm breeding zone thickness of 100% dense $LiAlO_2$ will correspond to a 46-cm breeding zone thickness with 60% dense $LiAlO_2$.

The neutronic performance parameters for the reference design with both the beryllium and Zr_5Pb_3 multipliers are listed in Table 11. Both designs achieve a tritium breeding ratio of ~1.2 but the beryllium design deposits more energy per fusion neutron due to the difference in the Q value of (n,2n) reaction cross sections for both neutron multipliers. However, the energy leakage, the neutron leakage, and the maximum lithium burnup are lower with the Zr_5Pb_3 multiplier, which is desirable from the shielding point of view.

The change in the blanket neutronic performance during the blanket life has also been analyzed to assure satisfactory performance. The neutronic performance of the STARFIRE reference design with the Zr_5Pb_3 neutron multiplier is almost constant during the blanket life of 6 yr or ~16.2 $MW\text{-}yr/m^2$ integrated neutron wall loading. The tritium breeding ratio drops by 0.7% at the end of life, while the nuclear energy deposition increases by 0.35% because of more neutron capture in the steel.

Table 10. Blanket Parameters for STARFIRE Reference Design

Zone Description	Zone Thickness (cm)	Zone Composition Percentage by Volume
First wall	1	50% PCA steel structure
		27% H_2O coolant
Neutron multiplier	5	100% Zr_5Pb_3 or 70% Be
Second wall	1	35% PCA steel structure
		17% H_2O coolant
Tritium breeder	30	80% $LiAlO_2$ tritium breeder[a]
		10% PCA steel structure
		5% H_2O coolant
		5% He purge stream
Reflector	15	90% C reflector
		5% PCA steel structure
		5% H_2O coolant

[a]Natural lithium for beryllium neutron multiplier or enriched 60% ^6Li for the Zr_5Pb_3 neutron multiplier.

Table 11. Blanket Neutronic Parameters for STARFIRE Reference Design Based on a One-Dimensional Model

Neutron Multiplier Material	Zr_5Pb_3	Be
Neutron multiplier material thickness (cm)	5	3.5
^6Li enrichment (%)	60	Natural
$^6Li(n,\alpha)T$ reaction per fusion neutron	1.186	1.142
$^7Li(n,n'\alpha)T$ reaction per fusion neutron	0.020	0.075
Tritium breeding ratio	1.206	1.217
Energy per fusion neutron (MeV)	17.44	19.87
Neutron energy leakage per fusion neutron (MeV)	0.041	0.057
Gamma energy leakage per fusion neutron (MeV)	0.036	0.085
Total energy leakage per fusion neutron (MeV)	0.077	0.142
Neutron leakage per fusion neutron	0.019	0.038
Maximum lithium burnup at 16.2 $MW\text{-}yr/m^2$ (%)	16.9[a]	21.8[a]
Average lithium burnup at 16.2 $MW\text{-}yr/m^2$ (%)	3.61	3.64

[a]Averaged over the first cm of the breeder zone.

The blanket neutronic performance with the beryllium neutron multiplier is more sensitive to the burnup of ^6Li during the blanket life. The burnup analysis for the beryllium blanket was performed in 3 MW-yr/m^2 steps for a blanket design slightly different from the reference design. The blanket parameters used in this burnup analysis included a higher H_2O fraction (50%) in the first wall, a thicker neutron multiplier zone (5 cm of 100% beryllium), and a thicker second wall (50% steel, 25% H_2O). The tritium breeding ratio and the nuclear energy deposition per fusion neutron are given in Fig. 14. The tritium breeding ratio shows a significant drop at the end of life (16.2 MW-yr/m^2 integrated neutron wall loading). However, for the STARFIRE reactor at any point in time, the average integral neutron wall loading will not exceed 8.1 MW-yr/m^2. These changes should be somewhat less for the reference blanket parameters.

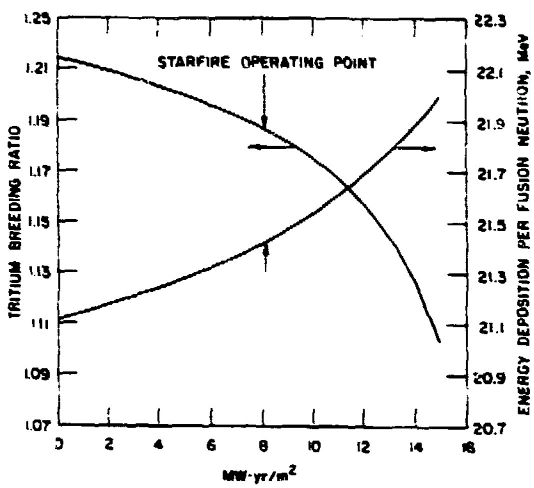


Fig. 14. Tritium breeding ratio and energy deposition per fusion neutron versus blanket exposure for beryllium neutron multiplier, $LiAlO_2$ tritium breeder, C reflector, H_2O coolant, and PCA structure.

The three-dimensional neutronic analysis was performed for the reference design to more accurately determine the nuclear energy deposition in each blanket component and net tritium breeding ratio. The Monte Carlo MORSE-CG code[6] was used for these calculations. A 67-multigroup cross-section set (46 neutron and 21 gamma) collapsed from the CTR library[7] with the P_3 approximation used for the calculations. The MACKLIB-IV[8] was employed to calculate the nuclear response functions.

The neutron source distribution for the calculations was determined from the fusion power density as a function of (r,z). It should be noted that the neutron source is shifted 79 cm from the geometrical center of the reactor chamber towards the outer blanket. The geometry model used in the calculation is shown in Fig. 15. The geometry of the blanket, the actual dimension of the individual zones, the limiter system, the rf system, and the geometry change in the poloidal direction are explicitly represented in the model. The inner blanket has a thickness of 28 cm (including 0.6 density factor for the tritium breeding material) with no reflector. The blanket and shield are included in the geometrical model. The Zr_5Pb_3 neutron multiplier option and the TA-5W limiter system are employed for the three-dimensional analysis.

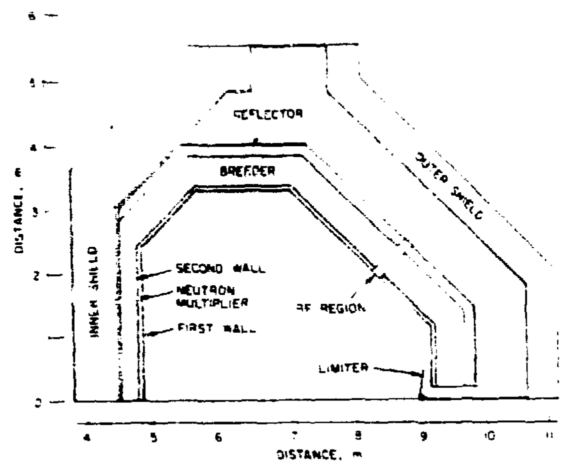


Fig. 15. Geometry model for three-dimensional neutronic analysis.

Table 12 gives the nuclear energy deposition in the different reactor components. The fractional standard deviation in the calculation is less than 5% for any component. As indicated in Table 13, the net tritium breeding ratio is 1.044 with a standard deviation of 0.29% for the reference design with Zr_5Pb_3 neutron multiplier option. The corresponding value from the one-dimensional model is 1.206 without the limiter and the rf system with an inner blanket thickness of 46 cm. The doubling time corresponding to a 1.044 net tritium breeding ratio is 1.5 and 3.1 yr for a tritium inventory of 5 and 10 kg, respectively.[9] It should be noted that the percentage of the H_2O coolant and the PCA structure are assumed to be uniformly distributed throughout the entire breeding zone in these calculations. Since the final thermal hydraulic analysis calls for less H_2O coolant and PCA structure in the tritium breeding zone, the net tritium breeding ratio should be slightly greater than 1.044.

Table 12. Nuclear Energy Deposition in Each Zone from the Three-Dimensional Analysis for the Reference Design with Zr_5Pb_3 Neutron Multiplier

Blanket Component	Energy per Fusion Neutron (MeV)	Fractional Standard Deviation
First wall	1.1913	0.0071
Neutron multiplier	3.2897	0.0086
Second wall	0.4072	0.0093
Tritium breeding zone	11.0070	0.0061
Reflector	0.1622	0.0431
Blanket jacket	0.0771	0.0337
Limiter system	0.8231	0.0402
rf system	0.1480	0.0455
Inner shield	0.1181	0.0613
Outer shield	0.2166	0.0573
Total	17.2923	

Table 13. The Net Tritium Breeding Ratio from the Three-Dimensional Analysis for the Reference Design with Zr_5Pb_3 Neutron Multiplier

Reaction Type	Energy per Fusion Neutron (MeV)	Fractional Standard Deviation
$^6Li(n,\alpha)T$	1.0216	0.0030
$^7Li(n,n'\alpha)T$	0.0225	0.0148
Tritium breeding ratio	1.0441	0.0029

Conclusions

The design of an optimized blanket for STARFIRE, a commercial tokamak fusion power plant, has been carried out. The analyses on the solid breeder blanket for the commercial reactor lead to the following conclusions: (1) the beryllium, lead, lead-bismuth, and bismuth neutron multipliers exhibit the highest tritium breeding ratios while the beryllium neutron multiplier produces the highest energy deposition per fusion neutron; (2) the use of H_2O as a coolant results in a lower tritium breeding ratio which limits the neutron multiplier choice to Pb, PbBi, Bi, Be, and Zr_5Pb_3; (3) the ^6Li burnup rate and the nuclear heat generation rate are more uniform with D_2O as a coolant; however, D_2O is very expensive compared to H_2O; (4) the desire to use solid neutron multiplier at practical coolant temperatures and the physical properties of the different neutron multipliers limit the choice to Zr_5Pb_3 or beryllium material; (5) no ^6Li enrichment is required for the beryllium neutron multiplier with $LiAlO_2$ solid breeder while the Zr_5Pb_3 neutron multiplier needs a 60% ^6Li enrichment; and (6) the rf and limiter systems, the spatial distribution of plasma neutron source, and the thickness restriction on the inner blanket result in a reduction in the tritium breeding ratio of ~13%.

Acknowledgment

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