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Nucleonic Aspects of Synfuel Blankets

University of California

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Nucleonic Aspects of Synfuel Blankets

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NUCLEONIC ASPECTS OF SYNFUEL BLANKETS

by

Donald J. Dudziak and Gene L. Woodruff

ABSTRACT

Studies of fusion reactors applied to synthetic fuel (synfuel) production have included detailed nucleonic analyses. Scoping studies were first performed to satisfy constraints such as net tritium breeding, and optimization of energy production in high-temperature vs moderate-temperature blanket regions. Detailed characteristics of a chosen reference design were then computed, including spatial distributions of kerma, dpa, hydrogen and helium production, and tritium breeding. The reference design provides a breeding ratio of 1.11 while depositing 42% of the recoverable energy in the high-temperature region used as a thermochemical process heat source. At a 1-MW/m^2 first-wall neutron loading, displacement damage and helium production in steel are a maximum of 11 dpa/yr and 111 appm/yr, respectively.

I. INTRODUCTION

Although the primary objective of the United States Department of Energy (US DOE) fusion program is commercial electric power production, there are compelling reasons to consider designs which produce nonelectrical energy. Only about 35% of United States energy consumption is electrical. Even if this percentage increases, as expected, the major portion remains nonelectrical (including essentially all of the transportation component.) Furthermore, early application of fusion energy may be significantly enhanced if the reliability constraints associated with operation on the electrical grid can be relaxed. The use of fusion power to produce synthetic chemical fuels (synfuel) meets both of these objectives. Synfuel could be quite versatile in satisfying a variety of energy demands and it represents a form of stored energy, so reliability specifications can be lowered.

It is reasonable to impose a requirement for net tritium breeding in a synfuel blanket if early application is an objective. Eventually, a sufficient number of fusion reactors may be operating to produce a surplus of tritium, thereby permitting some nonbreeding designs. The first group of fusion reactors, however, will almost certainly have to breed tritium.

Neither the type of synfuel to be produced nor optimized methods of production have yet been determined. A number of alternatives have been studied,[1] however, and it is clear that a very high temperature region (≳ 1 400 K) is a highly desirable feature of any thermochemical synfuel blanket. The desirability of this feature goes beyond efficiency relationships, because some thermochemical processes have temperature thresholds.

The twin requirements for both tritium breeding and a high-temperature region may not be achievable in a single zone of the blanket. It is likely that an inner tritium breeding region, operated at relatively low temperatures (~ 800 K), will be surrounded by a high-temperature region. A major objective of our first definitive synfuel blanket, therefore, is to achieve an adequate tritium breeding value in a

low-temperature region, while at the same time depositing a sufficiently large fraction of the energy in the high-temperature region. Follow-on studies will look at alternative blanket designs, which breed tritium in a very high-temperature region. Such design efforts are driven by the need for a larger fraction of the energy at high temperature than is available in the generic class of designs considered in this report.

This report describes a series of scoping calculations in which the trade-offs between tritium breeding and heating were studied. A semioptimized reference configuration is then analyzed in greater detail.

II. SCOPING STUDIES

A. Basic Configuration

The basic configuration used in the scoping studies is illustrated in Fig. 1. Steel is used as the first-wall material and for structure throughout. A neutron multiplier of variable thickness is adjacent to the first wall followed by the breeding region and then by a graphite high-temperature outer blanket.

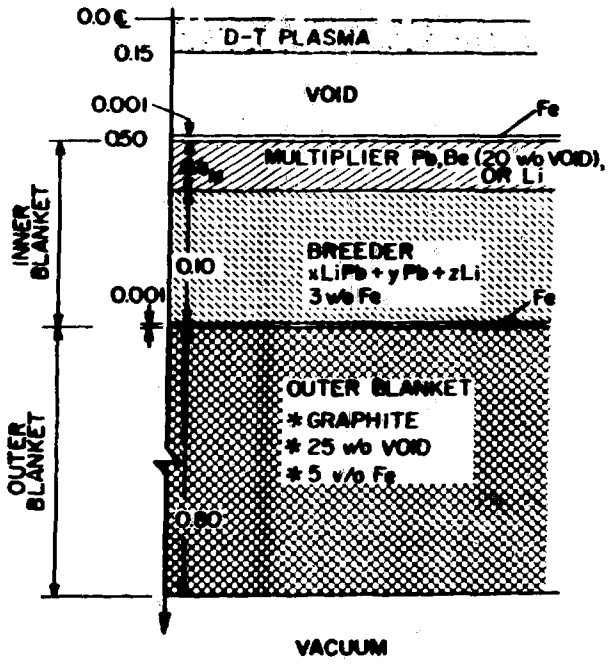

Fig. 1. Schematic diagram of neutronics blanket model(s) used to examine trade-offs between tritium breeding in a (low-temperature) inner region and the energy deposited into a (high-temperature) outer region.

Materials considered for the multiplier included Be, Li, Pb, and combinations of Li and Pb. In all probability the use of Be is not presently an acceptable option for reasons of perceptions concerning resource limitations, fabrication difficulty, and toxicity. It is the most effective of all multiplier materials, however, with the exception of the fissionable isotopes, and provides a useful standard of comparison.

The breeding region is basically a Li region. Compositions which include LiPb were also considered, however, because the Pb might provide some secondary neutron multiplication and because the physical properties of LiPb might prove to be attractive.[2] All mixtures of LiPb and Pb are stated in terms of at.% of LiPb in the mixture.

Graphite is an obvious choice for the outer blanket by virtue of its high-temperature capabilities, low cost, neutronic properties, and ease of fabrication. For the scoping studies a 25% void was included to allow for gas cooling and 5% steel represented structural requirements.

The plasma was assumed to have a 0.15-m radius surrounded by a vacuum thickness of 0.35 m. The results of the calculations presented here are not very sensitive to the first-wall radius. It should be noted, however, that the blanket configuration is somewhat idealized. Various design requirements related to plasma confinement and/or heating could invoke penalties in nucleonic performance. Examples include ISSEC - type protective layers inside the first wall,[3] presence of magnets adjacent to the first wall, or significant neutron leakage through vacuum or beam injection ports (or through nonexistent inner blankets, such as in low aspect ratio Tokamaks.) If such features are required, the breeding region will have to be increased in size and the percentage of the total energy deposited in the outer blanket will be reduced.

All of the nucleonic calculations described below were performed with the diffusion synthetic, discrete-ordinates code, ONETRAN-DA.[4] The S_8 quadrature was that for cylindrical geometry in the code library, while P_3 cross sections and kerma-factor data were obtained from the MATXS file.[5]

B. Scoping Results

The results of the scoping calculations are shown in Fig. 2, for a 0.1-m breeding region following

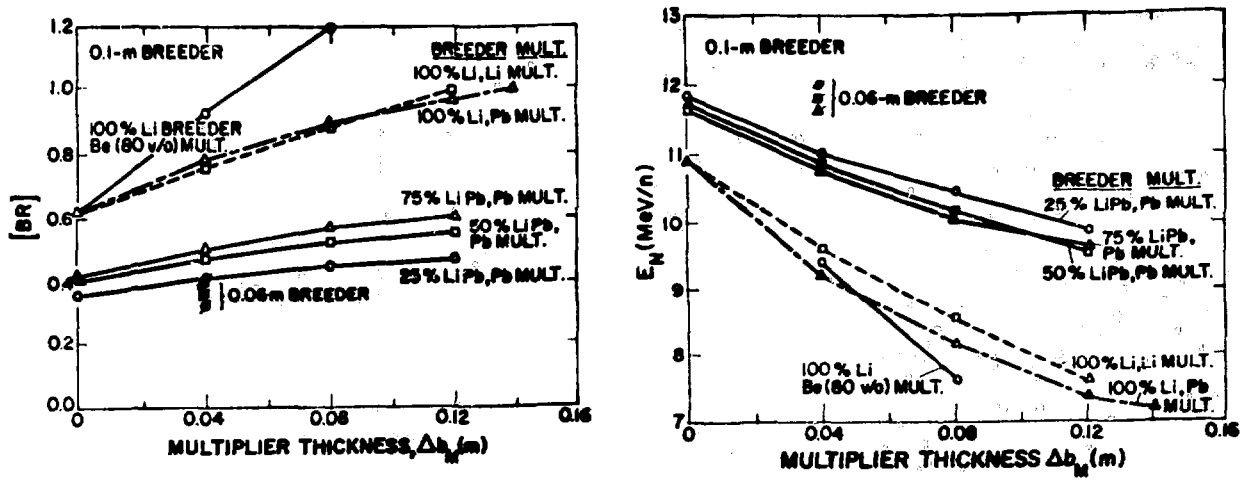

Fig. 2. Dependence of tritium breeding ratio [BR] and energy deposited into the outer graphite region E_N on neutron-multiplier thickness for a range of breeder/multiplier compositions (Re: Fig. 1).

a multiplier region of varying thickness. In the left portion of Fig. 2 the tritium breeding ratio, [BR], is plotted as a function of multiplier thickness for various multiplier and breeder region compositions. In the right portion the energy deposited per fusion neutron, E_N (MeV/n), is plotted for the same configurations.

The results shown in Fig. 2 may be grouped into four categories:

	Multiplier	Breeder Region
(1)	Be (80 vol%)	Li
(2)	Li	Li
(3)	Pb	Li
(4)	Pb	LiPb & Pb

The general pattern for all of these categories is very similar. As the multiplier thickness is increased, [BR] increases and E_N decreases. In general, categories having higher [BR] values for a given multiplier thickness have lower E_N values relative to the other categories.

The most effective multiplier is Be. A [BR] value of unity can be obtained with a thickness of about 0.05 m. The Li-Li combination, category (2), is the next most effective combination. The improvement over category (3) is not large, but it is noteworthy that the improvement includes both [BR] and E_N. The least effective combination is category (4) and within this group [BR] decreases as the percentage of Li decreases.

These results suggest a decreasing ranking of Be, Li, and Pb for use as multiplier materials. Such a ranking is also consistent with a comparison of the Q values for the relevant reactions as shown below:

Reaction	Q Value (MeV)
$^{9}Be(n,2n)^{8}Be$	(-) 1.67
$^{7}Li(n,n't)^{4}He$	(-) 2.47
$^{208}Pb(n,2n)^{207}Pb$	(-) 7.37

Larger negative Q values have an adverse effect, both in terms of higher threshold energies and in net energy deposition per fusion. A higher threshold energy limits the fraction of the neutron spectrum which can contribute to neutron multiplication or, in the case of ^{7}Li, tritium production with no net change in neutron population. The usefulness of Pb as a neutron multiplier is, therefore, limited to the innermost portions of the blanket. The [BR] curves in Fig. 2 for category (4) have already become relatively flat for a multiplier thickness of 0.12 m, and it is clear that for this breeder region configuration, a [BR] value of unity cannot be achieved for any multiplier thickness. The effect on energy deposition of the large negative Q for Pb is somewhat mitigated by the reduced energy transfer through elastic and inelastic scattering. The fraction of the total energy deposited in the outer blanket is significantly higher for the configurations containing

high concentrations of Pb, as can be seen in the right-hand side of Fig. 2.

III. REFERENCE CONFIGURATION

A. Description

Based on the results of the scoping calculations a Li-Li combination was selected as the reference configuration. The multiplier and breeder regions are, therefore, effectively one larger zone of Li. The reference configuration also differs from Fig. 1 in two other respects. A 40-mm vacuum was introduced between the Li and C zones in order to reduce conduction heat loss from the high-temperature C zone. The vacuum is separated from the Li zone by 2.5 mm of steel (representing a structural wall and foil thermal insulation) and from the C by 1.0 mm of steel. The second difference is a reduction in the concentration of steel in the Li zone from 3 vol% to 1 vol%, based upon realistic structural design calculations.[6] This latter change increases [BR] by approximately 1%. Figure 3 shows a schematic radial traverse of this reference configuration selected for further detailed analysis.

B. Results

The reference configuration described above produces an acceptable value for [BR], namely, 1.11, when the Li zone has a thickness of 0.26 m. The corresponding energy deposition in the graphite region E_N is 7.14 MeV/fusion neutron. Figure 4 illustrates the variation of [BR] with the total Li-region thickness.

The spatial distribution of the power density is given in Fig. 5, normalized to a first-wall loading of 1.0 MW/m^2. The variation in the graphite region is fairly large, involving a max/min ratio of about 24. The power density is relatively low, however, and it should not be difficult to achieve uniform outlet temperatures.[6] The void fraction could be made spatially dependent with larger values in the inner locations. This would also reduce the gradient in the power density.

Again normalized to a first-wall loading of 1.0 MW/m^2, the total energy deposition in each region was computed. Table 1 presents the results of these calculations, along with the total energy deposited in the reactor configuration shown in Fig. 3. The heating values are given in units of kW per meter of length along the cylindrical axis.

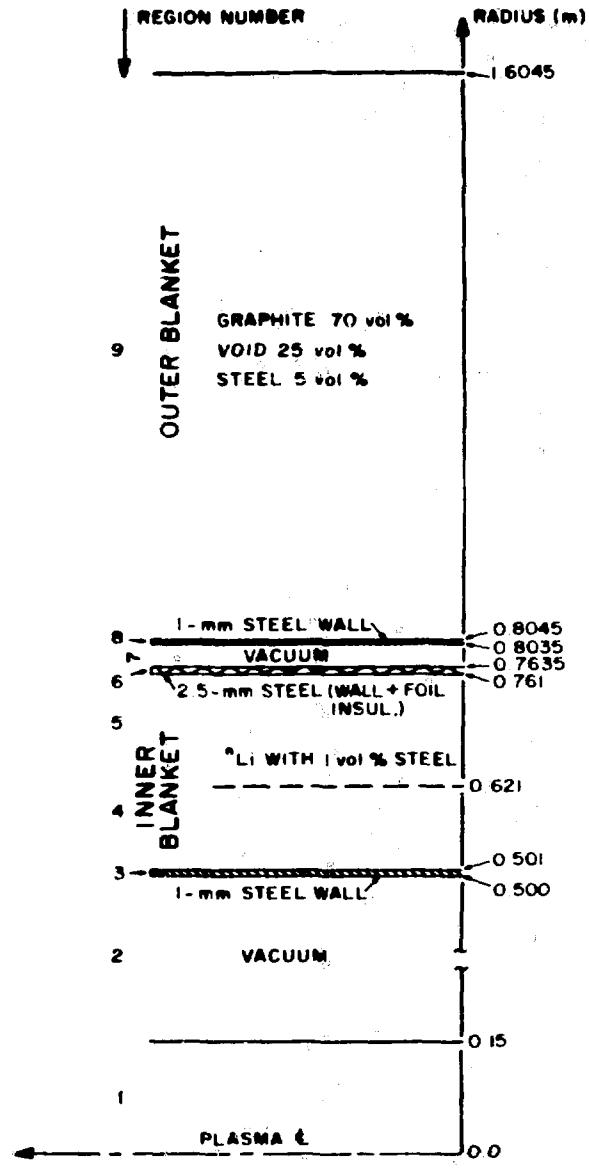

Fig. 3. Reference blanket model resulting from parametric scoping study.

Comparing the total energy deposited (kerma) with the kinetic energy of the fusion neutrons emitted in the plasma (3.183×10^3 kW/m) reveals an energy multiplication factor of 1.19, or 2.67 pJ (16.7 MeV) per fusion neutron. Adding to this the potential energy of the 0.0678 fractional neutron leakage, assuming a binding energy of ~ 1.3 pJ per neutron, gives a total of 2.76 pJ per fusion neutron. Kinetic energy of the leaking neutrons is ignored in this latter energy calculation because the neutron leakage spectrum is predominantly thermal. Similarly, adding

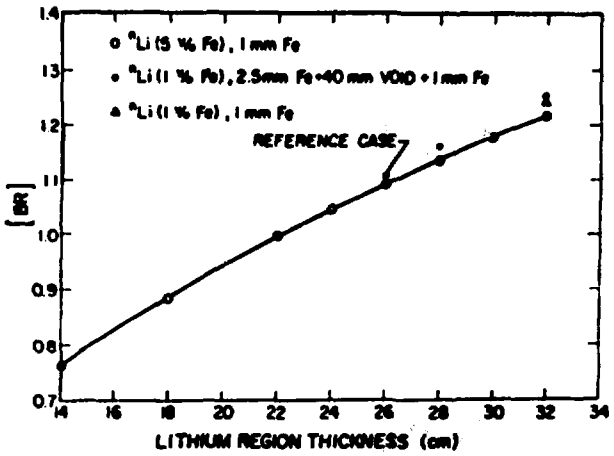

Fig. 4. Variation of tritium breeding ratio with Li region thickness.

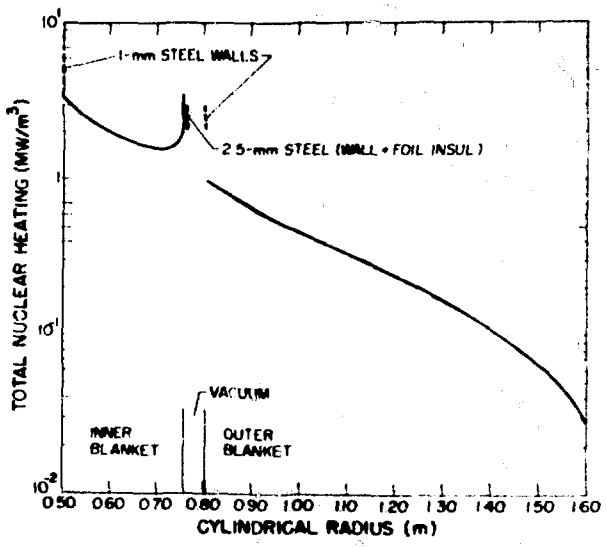

Fig. 5. Spatial dependence of the power density in the reference blanket (of Fig. 3) for I_w = 1 MW/m^2.

the 0.043-pJ gamma-ray leakage per fusion neutron provides a total energy accounting of ~ 2.80 pJ (17.5 MeV) per fusion neutron. No account is taken for decay energy of activation products; i.e., delayed kerma. Also, from Table I we find that 42.2% of the recoverable energy deposition occurs in the high-temperature graphite region and its adjacent 1-mm steel wall.

One area of some concern in the reference blanket design was the assumption concerning the volume percent Fe in the ^{6}Li breeding zone. Although, as noted above, a detailed blanket structural analysis demonstrates the adequacy of 1 vol% Fe, provision may have to be made for vacuum ports or other structural metal in this region. Thus, a sensitivity study was performed for volume percents of Fe ranging from 0.0 to 10. The results for tritium breeding in ^{6}Li, ^{7}Li, and total Li are shown in Fig. 6 for 0.0 to 5.0 vol%Fe. All results are percentage changes relative to the reference blanket, i.e., 1 vol% Fe. It is interesting that although [BR] decreases monotonicall

TABLE I

NEUTRON, GAMMA-RAY AND TOTAL KERMA IN EACH REGION OF THE REFERENCE CONFIGURATION (kW/m)

Region (cf. Fig. 3)		^{6}Li		^{7}Li		C		Fe		
No.	Description	n	γ	n	γ	n	γ	n	γ	TOTAL
1,2	Vacuum									
3	1-mm steel wall							1.072+1	9.110	1.983+1
4	^{n}Li, 1 vol% steel (0.12 m)	2.814+2	3.89	6.913+2	4.803+1			8.777	1.141+1	1.0448+3
5	^{n}Li, 1 vol% steel (0.14 m)	4.910+2	5.06	5.032+2	6.242+1			5.552	1.484+1	1.0820+3
6	2.5-mm steel							7.234	2.829+1	3.552+1
7	vacuum	-	-	-	-	-	-	subtotal, low temp.		2.1822+3
8	1-mm steel wall							2.831	1.187+1	1.470+1
9	graphite/void/steel					5.324+2	7.088+2	2.805+1	3.108+2	1.5801+3
								subtotal, high temp.		1.5948+3
								GRAND TOTAL		3.777+3

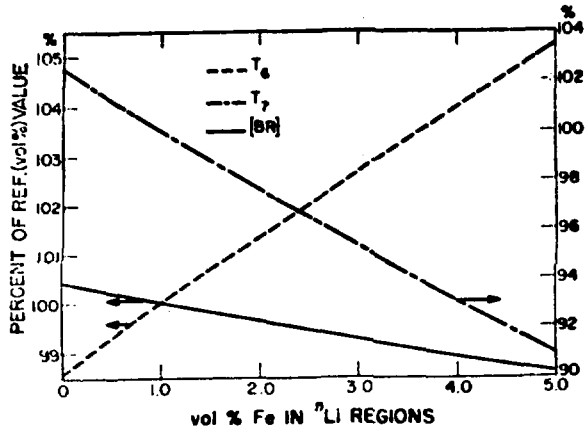

Fig. 6. Effect of vol%Fe in inner blanket region on tritium breeding ratio, for the reference blanket model (cf. Fig. 3).

with vol%Fe, the T_6 portion increases monotonically. Examination of the detailed spectrum and energy dependent ^{6}Li(n,t)^{4}He reaction rates reveals that the latter effect is due to spectrum softening in the ^{7}Li region by the added Fe, which causes increased ^{6}Li absorption far outweighing the loss in ^{6}Li atom density and increased absorption in Fe. This same softening effect is what decreases the ^{7}Li(n,n't)^{4}He reaction rate, in addition to that caused by decreased ^{7}Li atom density.

As input for radiation damage analysis, calculations were performed to determine displacements *per atom (dpa), hydrogen, and helium production* rates. Spatially dependent rates were determined for all three reactions in the steel, and for dpa and helium production in graphite (hydrogen producing reactions do not occur for neutron energies < 14 MeV). Figure 7 shows the resultant data for the steel, *all normalized to a 1-MW/m^2 first-wall loading.* Helium production in the graphite varied from 44.1 to 0.29 appm/y, from the inner to outer edges of the outer blanket (i.e., from 0.8045 to 1.6045 m), whereas displacements varied in the same region from *2.97 to 0.024 dpa/y.*

IV. CONCLUSIONS

It is possible to design fusion blankets for synfuel production which incorporate a tritium breeding ratio greater than unity and in which the fraction of the total energy deposited in the high-temperature region is approximately 50%. The cases

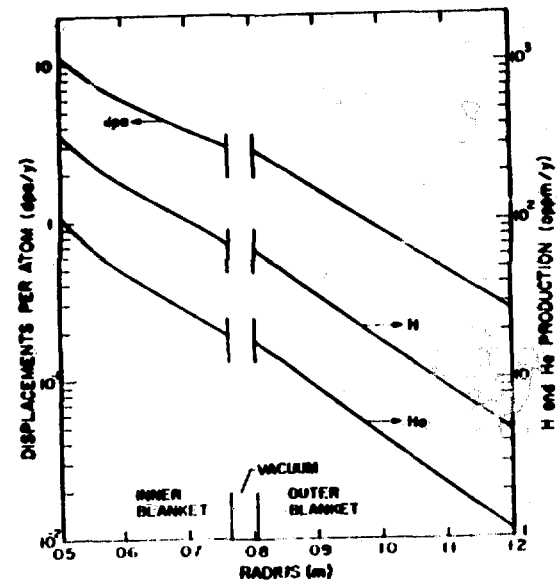

Fig. 7. Spatial distribution of H, He, and dpa rates in steel, at *1 MW/m^2 wall loading.*

described here are somewhat idealized in that they do not include features which might be required for plasma heating and/or confinement and which could compromise blanket performance.

The portion of the energy deposited in the Li breeding region can and probably should be used to produce electricity to provide recirculating power for the plasma, as well as some of the lower temperature enthalpy required by the thermochemical load distribution. The design described here couples very well with a fusion reactor design having a recirculating power fraction of approximately 0.5 or less.

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ADDENDUM

After the calculations described herein were performed, two laboratories independently reported experimental results and calculations which appear to indicate that errors exist in the available cross-section data for the $^7Li(n,n't)^4He$ reaction.[7,8] The discrepancies which have been reported suggest that this cross section is about 15% too high at 14 MeV and that the error decreases as neutron energy decreases. Such a discrepancy is also consistent with results reported by Reupke and Muir.[9] The effect of correcting this cross section on the tritium production rate will depend on the design. The ones most affected will be those with large amounts of natural Li located near the source of 14-MeV neutrons. The configuration reported here is an example of this type and our results could be significantly affected. The ^7Li contributed approximately 46% to the total tritium production rate, so that a reduction of 15% (which may slightly overestimate the correction required since not all of the reactions are due to 14-MeV neutrons) could reduce the total tritium breeding ratio by about 7%. This in turn could force an increase in the thickness of the Li inner blanket and further reduce the percentage of the total energy which is deposited in the high-temperature region. Based on the results shown in Fig. 2, the 42% value (of the total energy) noted above might be reduced to approximately 36%.

In Ref. 7 it is also concluded that calculated values of the ^7Li contribution to tritium breeding should be further reduced due to inadequacies in the treatment of inelastic scattering in ^7Li. Such a correction would be consistent with the well-known limitations of the ENDF library format. However, no other cases of significant discrepancies attributable to this effect have been reported.

A similar situation exists with respect to the treatment of inelastic scattering in ^6Li. In an effort to improve the accuracy of calculations involving inelastic scattering in ^6Li, a modified scattering matrix has been developed which is based on "pseudo levels" in ^6Li.[10] The effects of this phenomenon can be tested by performing two sets of calculations for a given assembly: one with the group constants obtained from the standard ENDF library, and another with the group constants containing the modified scattering matrix for ^6Li. We have performed such comparisons for three different assemblies:

(1) the reference configuration described here,
(2) a ^6Li metal sphere, and
(3) a sphere of ^6LiD.

In none of these cases was there a large effect. Typically, the tritium breeding ratio increased in ^6Li and decreased in ^7Li, both by roughly 1%. These results do not, of course, eliminate the possibility that the treatment of inelastic scattering in ^7Li could have a greater impact.

Further investigations of both the cross section for the $^7Li(n,n't)^4He$ reaction and the effects of more accurate treatment of inelastic scattering in ^7Li are clearly warranted.

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