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A HIGH PERFORMANCE, SUPPRESSED-FISSION ICF HYBRID

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Abstract

The neutronics aspects of an ICF hybrid concept are discussed. The breeding blanket consists of a beryllium neutron multiplier, metallic thorium fertile fuel and a liquid-lithium coolant. The fertile fuel fraction is 30 vol%, which is much higher than previous one-zone, suppressed-fission hybrid concepts. Fission in the bred ^{233}U is suppressed by competition from tritium breeding reactions in ^{6}Li. The total breeding ratio, T + F, is 2.05, and the total neutron energy deposited is 41.1 MeV per DT neutron. The 800-MW (fusion) hybrid produces ~3500 kg of ^{233}U per full-power-year.

Introduction

Fusion-fission hybrids have been classified into two basic categories: fast-fission and suppressed-fission.[1-4] In a fast-fission hybrid blanket the DT fusion plasma is surrounded by a region of ^{238}U or ^{232}Th. The 14-MeV fusion neutrons cause fast fission reactions in these materials and thereby increase the number of neutrons available for breeding fissile fuel and tritium.

Suppressed-fission hybrids depend on nonfissioning neutron multipliers such as Pb, Be or ^{7}Li to increase the number of neutrons available for breeding. (^{7}Li can be considered a neutron multiplier in this application since the $^{7}Li(n,n'T)\alpha$ reaction gives one of the desired products, T, and yet does not deplete the number of available neutrons.) Two basic configurations have been proposed for suppressed-fission blankets: the first is a two-zone blanket; the second is a one-zone, homogeneous blanket. In the two-zone blanket, neutron multiplication and tritium breeding occur in the first (inner) zone while fissile breeding occurs in the second (outer) zone. The first zone also moderates the neutrons, thus minimizing fast fission in the

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fertile zone. In the one-zone blanket, fast-fissioning is suppressed by fertile dilution; i.e., the concentration of fertile material is low (< 5 vol%). The majority of the blanket is comprised of neutron multiplying, neutron moderating and tritium breeding materials.

In both types of suppressed-fission blankets, thermal and epithermal fission of the bred fissile fuel is suppressed by maintaining a low fissile enrichment (~0.5%). In general, this requires frequent or even on-line reprocessing.

In this paper, a new regime for a one-zone, suppressed-fission hybrid is discussed. The concept is to suppress fission in the bred fissile fuel through competition for neutrons with ^{6}Li tritium breeding reactions. We find that the total fission rate in the proposed Be/Li/Th (with 0.5% ^{233}U) blanket goes through a maximum at ~5 vol% Th. At ~30 vol% Th, the fast fission rate in Th is nearly as great to the fission rate in the bred ^{233}U, but the total fission rate is less than in a blanket with only 2 vol% Th.

Another important finding is that there are significant resonance effects. Neutronic results from TART [5] were compared with those from ALICE.[6,7] Both codes are Monte Carlo codes utilizing the ENDL cross section library.[8] ALICE, however, uses a multiband method which gives a better treatment of resonance self-shielding effects. For the Be/Li/Th blanket investigated, ALICE predicts a lower fissile breeding rate, higher parasitic capture rate and higher fission rate in ^{233}U than TART. All these factors reduce the suppressed-fission hybrid performance. These findings are consistent with those of Taczanowski.[9]

Chamber Concept

The hybrid chamber is shown in Figs. 1 and 2. The fusion target is surrounded by an array of Be columns. These 8-m-high columns are made up of individual blocks, 67-cm-high and 40 cm in diameter, held together with steel fastening bands. A dense array of coolant channels is machined into each block. Each channel can accommodate a steel-clad, Th-metal, fertile-fuel pin. The Li coolant is supplied at the top of the chamber, traverses through the Be columns and exits at the bottom of the chamber. The columns are

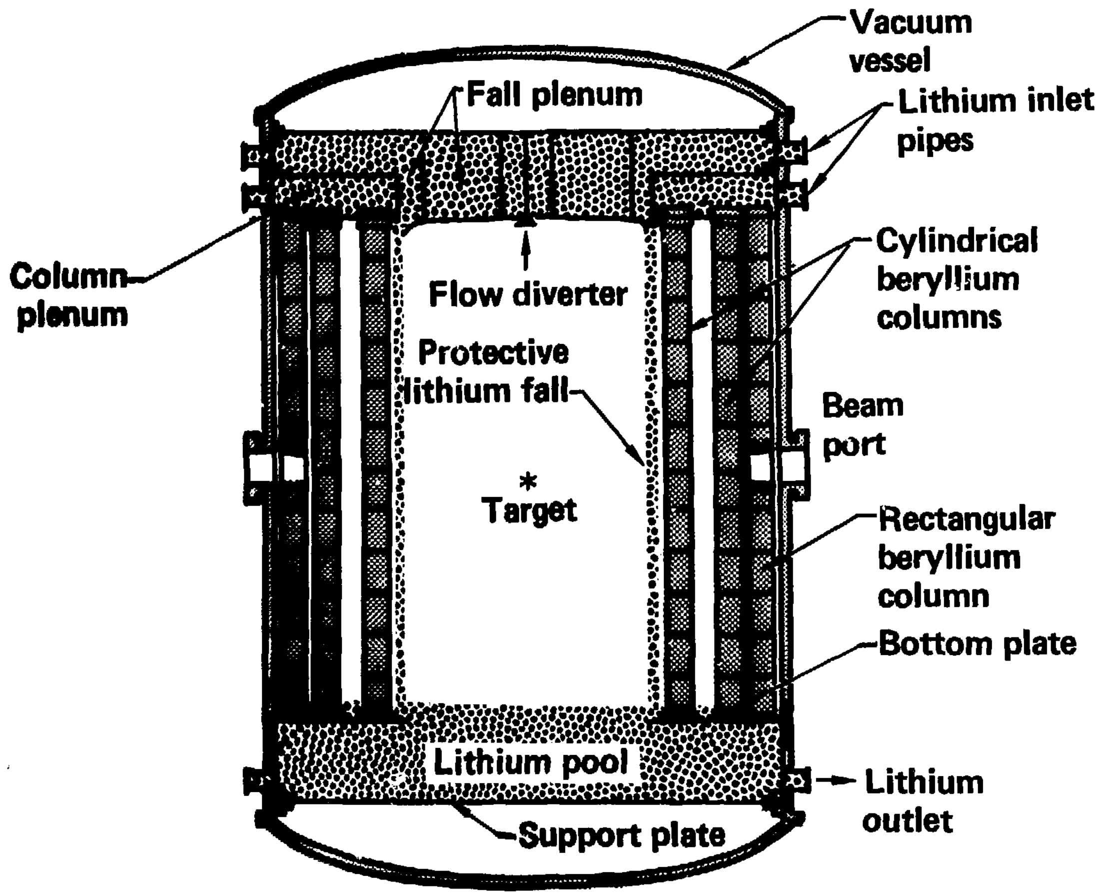

Fig. 1 The ICF hybrid design uses a Be multiplier.

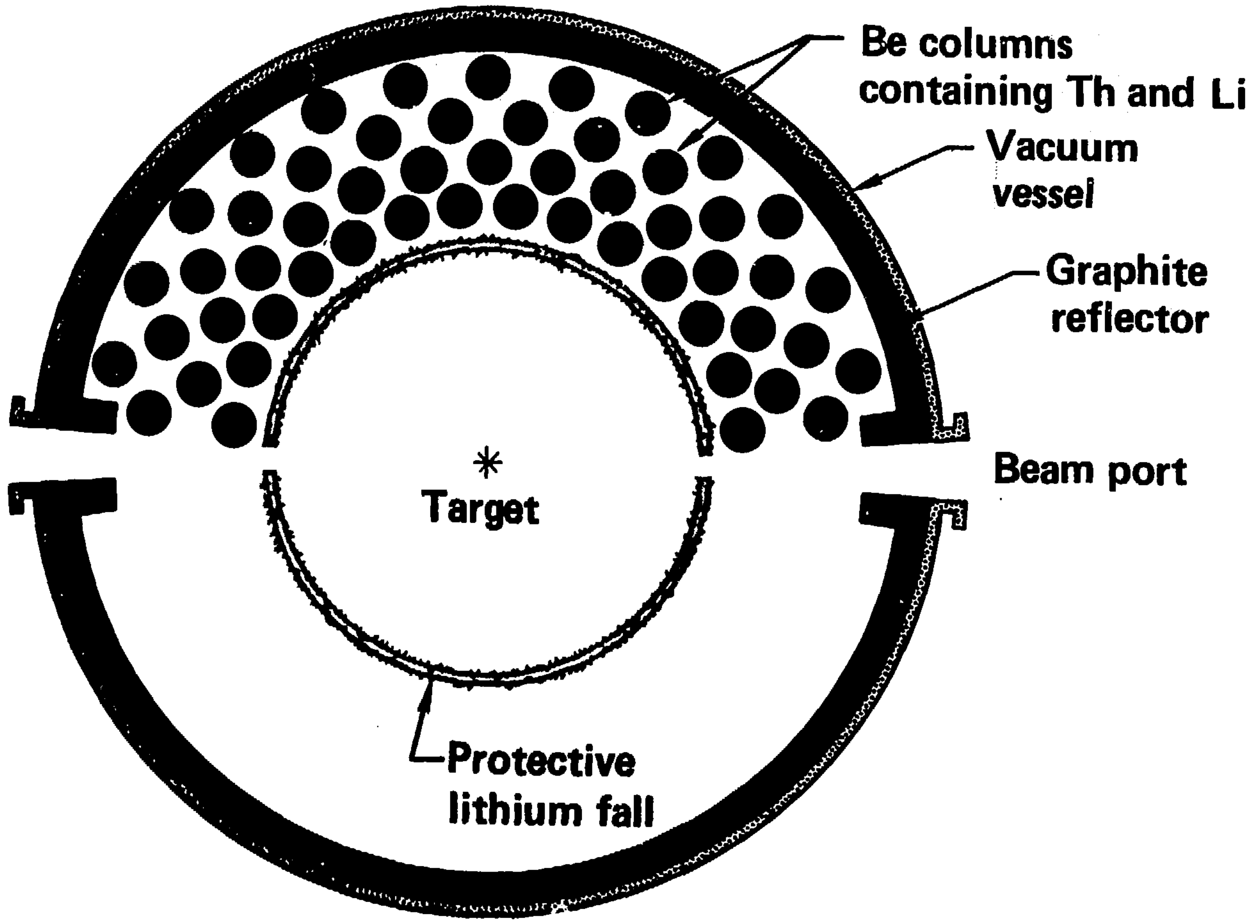

Fig. 2 Cross section of the hybrid reactor.

attached to top and bottom plates in such a way as to tolerate radiation-induced swelling and the vibrations resulting from each microexplosion.

A thin (~10-cm thick) Li fall region protects the Be columns from direct exposure to the x rays and debris emitted by the target. While shown as a continuous curtain, the protective fall could be composed of a couple rows of small diameter jets.

The fusion energy yield per pulse is 400 MJ, and the pulse repetition rate is 2 Hz giving a fusion power of 800 MW. This chamber design is adapted from a concept developed by TRW in conjunction with LLNL for a pure fusion reactor.

One-Dimensional Neutronics

A spherical model of the blanket was used for neutronic scoping studies. ALICE, the multiband version of TART, was used for these calculations. The model consisted of a 14.1-MeV neutron source distributed in a region of compressed DT ($\rho R = 3.0$ g/cm^2), a 10-cm-thick lithium region from 1.9 to 2.0 m and the breeding blanket from 2.0 to 4.0 m. The breeding blanket was at 50% normal density to account for the fact that the array of Be columns has a 50% packing fraction. The breeding blanket composition by volume fraction was:

Li	20%	constant
Fe	2%	constant
Be + Th	78%	

The blanket performance as a function of the Th volume fraction was investigated. As the Th fraction was increased the Be fraction was decreased such that the total of the two was always 78 vol%. The ^{6}Li concentration in lithium was adjusted to achieve a tritium breeding ratio somewhere between 1.0 and 1.1. In all cases the Th contained 0.5% ^{233}U to represent an average fissile enrichment, assuming a discharge enrichment of ~1%.

Figure 3 shows the total breeding ratio, T + F, and the fusion energy multiplication factor, M_f, as a function of the Th vol%. T is the sum of ^{6}Li(n,T)α reactions and ^{7}Li(n,n'T)α reactions per DT neutron. The net fissile breeding ratio, F, is given by

$$F = N\left[{}^{232}Th(n,\gamma)\right] - N\left[{}^{233}U(n,f)\right] - N\left[{}^{233}U(n,\gamma)\right] ,$$

where N is the number of indicated reactions per DT neutron. The fusion energy multiplication factor is

$$M_f = (E_n + 3.5)/17.6 ,$$

where E_n is the total neutron energy deposited per DT neutron. Note that E_n includes the neutron energy deposited in the compressed DT-fuel target.

As shown in Fig. 3, the breeding ratio increases rapidly with increasing Th content and then levels off beyond ~5 vol% Th. The fusion energy multiplication factor peaks at ~5 vol% Th and then falls, rapidly at first then gradually, as the Th content is increased beyond 5 vol%.

The peak in the energy multiplication is related to the variation in the fission rate in the breeding blanket. Figure 4 shows the number of $^{232}Th(n,f)$, $^{233}U(n,f)$, total fissions, and $Fe(n,\gamma)$ reactions per DT neutron. The Th(n,f) rate increases linearly with increasing Th content as expected. The $^{233}U(n,f)$ rate initially increases very rapidly but then falls beyond ~5 vol% Th. The total fission rate also goes through a maximum and then begins to level out at ~30 vol% Th where the number of Th fast fission reactions is approaching the number of $^{233}U(n,f)$ reactions.

The reason for this drop in ^{233}U fission rate can be understood if we examine how the ^6Li content varies with Th vol%. Recall that the ^6Li concentration was varied to give a tritium breeding ratio of ~1. Table 1 gives the atomic percent ^6Li in Li and also the ratio of ^{233}U atoms to ^6Li atoms in the blanket. The ^6Li fraction increases monotonically with Th vol%, but the ratio of $^{233}U/^6Li$ reaches a peak at ~5 vol% Th. Therefore, the competition between neutron absorption in $^6Li(n,T)\alpha$ reactions and $^{233}U(n,f)$ reactions governs the noted behavior of the total fission rate and M_f. Also note that the number of parasitic capture reactions in Fe drops off rapidly as Th vol% increases. This is another benefit of higher ^6Li concentrations.

Previous one-zone, suppressed fission blanket designs had low Th fertile contents, thus operating to the left of the peak in M_f (or total fissions).

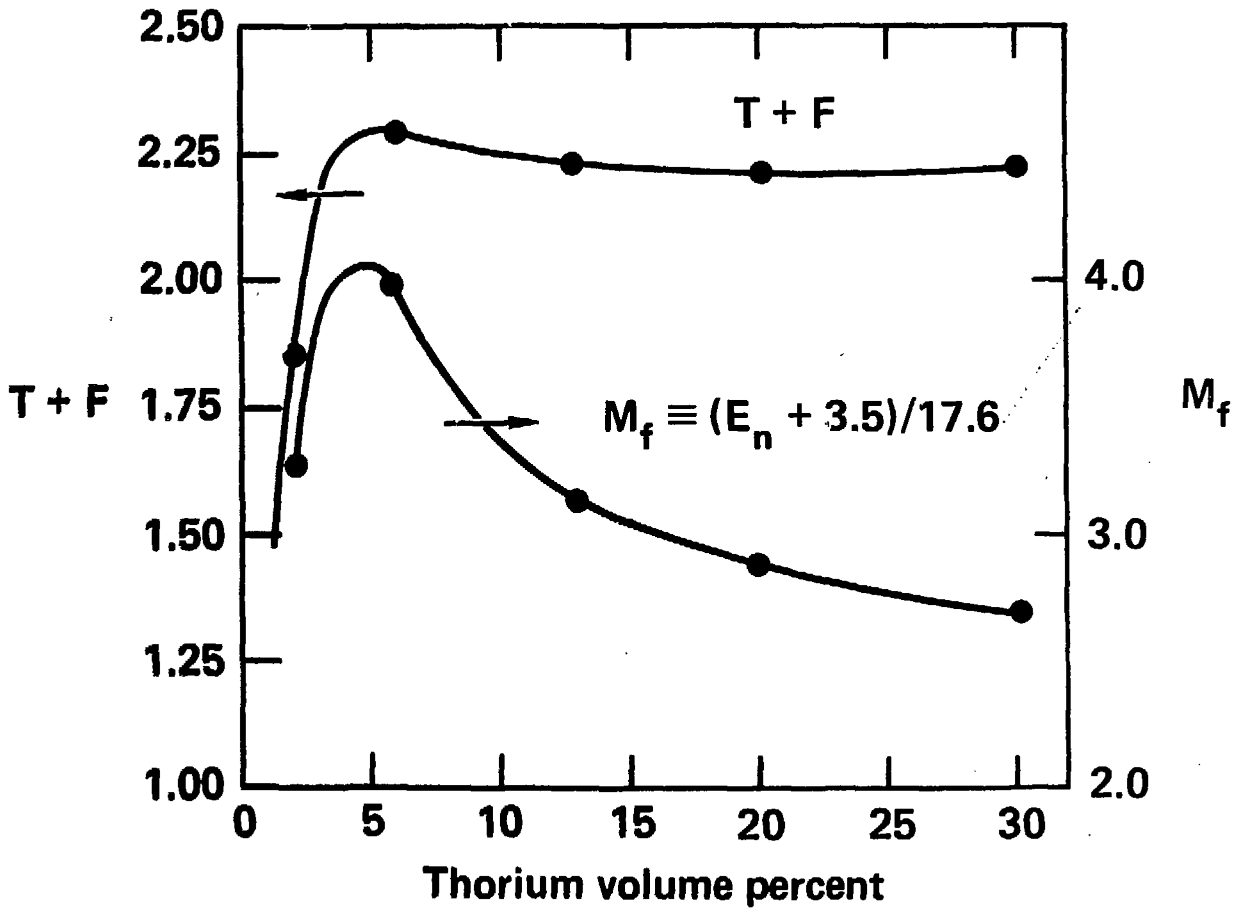

Fig. 3 Total breeding levels off and energy multiplication decreases beyond 5 vol% Th.

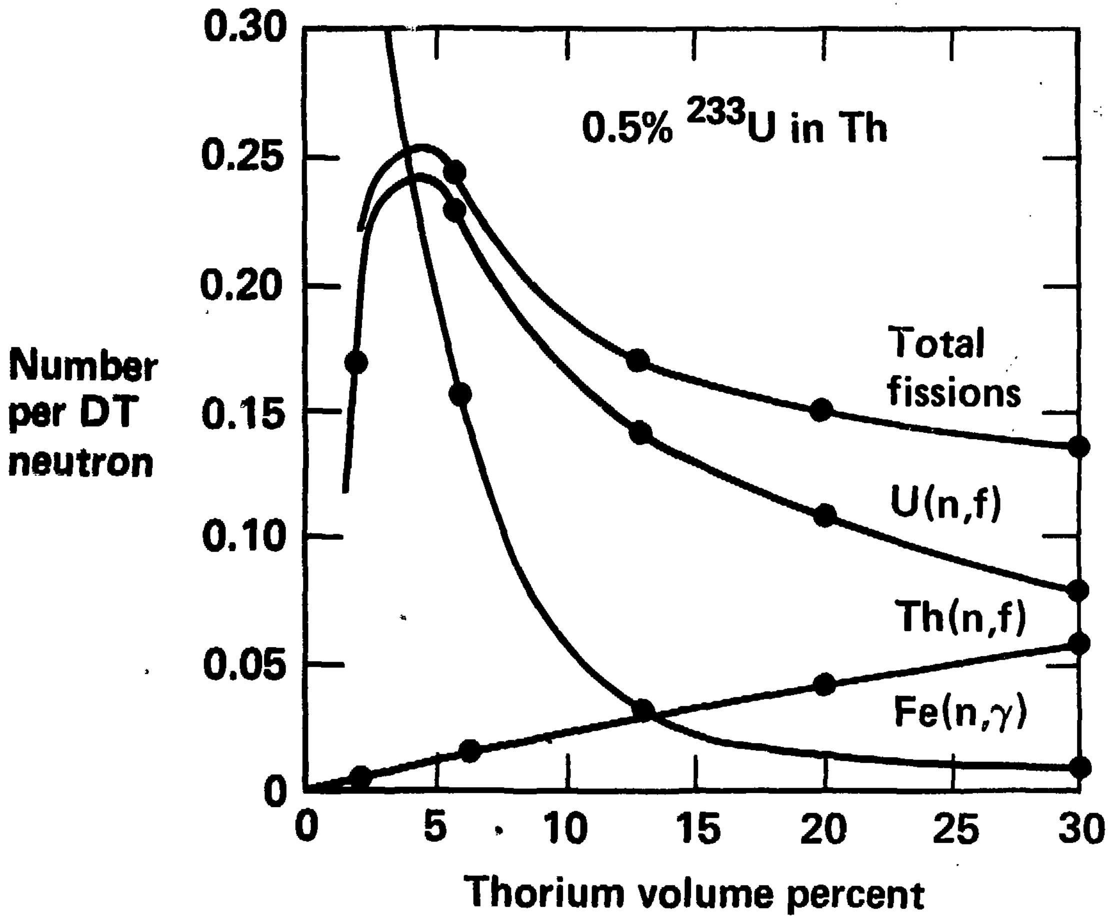

Fig. 4 Increasing the Th fraction reduces parasitic capture in Fe and fission in U-233.

Table 1. ^{6}Li Enrichment and Ratio of ^{233}U to ^{6}Li

Th Vol %	$^{6}Li/Li$ %	$^{233}U/^{6}Li$
2	0.08	0.44
6	0.20	0.53
13	1.20	0.19
20	3.00	0.12
30	8.00	0.07

In this study, we propose a blanket that has ~30 vol% Th and operates to the right of the peak in M_f.

The fissile production rate per unit of thermal power is sometimes used as a figure of merit for the hybrid since it is proportional to the thermal support ratio (i.e., the fission power that the hybrid fuels divided by the hybrid power). The specific production rate, g(^{233}U)/kW_t·yr, is equal to 4.35 F/M_f. In Fig. 5 (T + F − 1)/M_f is shown as a function of the Th vol%. Note that T + F − 1 gives the potential F if T was exactly 1.0. (This removes slight differences in T achieved in the various cases.) As seen, the specific production rate increases with increasing Th vol%. Some of the 1-D results are tabulated in Table 2 for reference.

Two-Dimensional Neutronics

A two-dimensional model of the chamber is shown in Fig. 6. In the radial direction there is a 0.1-m-thick Li fall at R = 1.9 m, followed by a 1.3-m-thick breeding blanket. There is a 0.3-m-thick graphite reflector at R = 4.0 m, and a 5-cm-thick steel vessel wall outside of that. Above the ρR = 3 g/cm^2 DT target is a 2-cm-thick steel top plate, a 1-m-thick lithium zone representing the inlet plenum and a 5-cm-thick steel vessel wall. Below the target is the 1-m-thick lithium outlet plenum and a steel wall.

The material compositions are given in Table 3. The breeding blanket is 20 vol% Li (5% ^{6}Li), 48 vol% Be, 2 vol% Fe and 30 vol% Th (0.5% ^{233}U). The 1.3-m-thick breeding blanket is divided into six zones to reveal variations as a function of depth into the blanket. The inner two zones are each 13-cm thick, while the outer four are each 26-cm thick. All breeding blanket zones are at 1/2 normal density to account for the 50% packing fraction of the Be columns in the blanket.

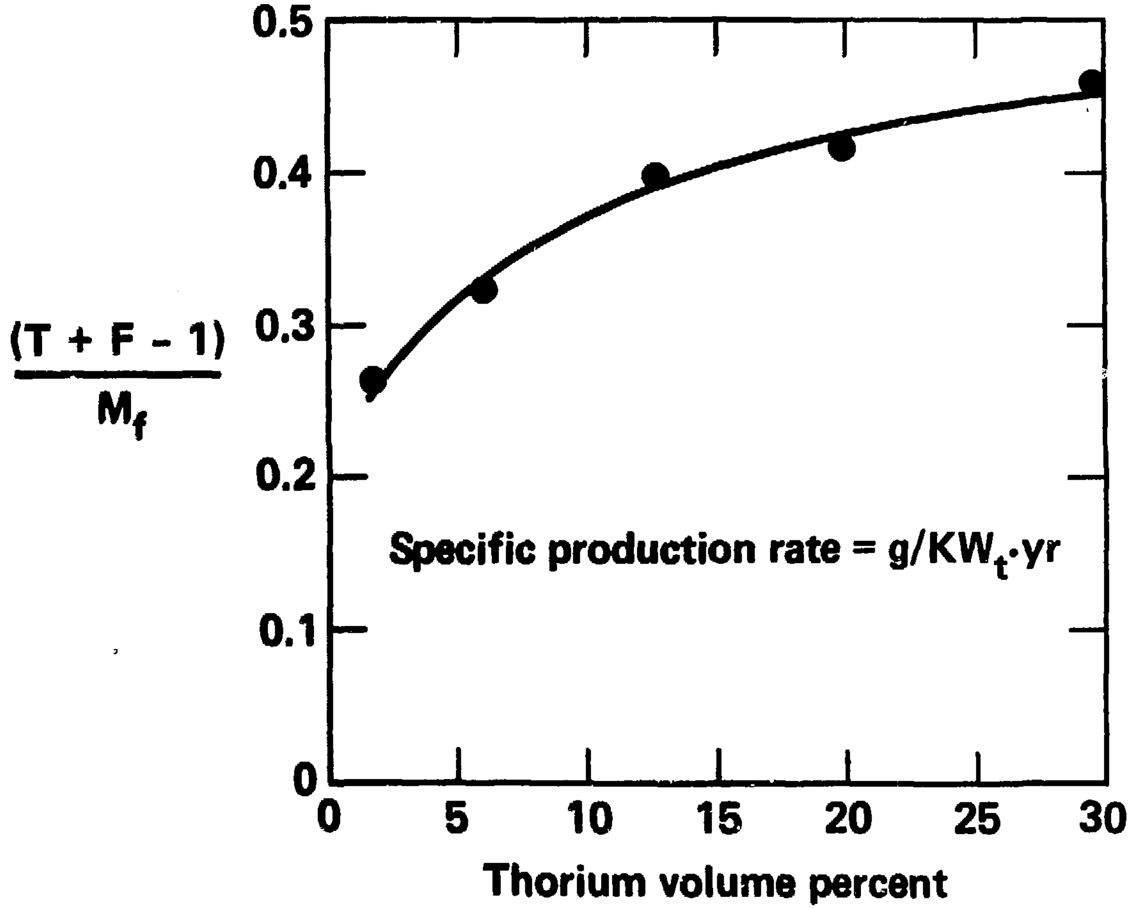

Fig. 5 The specific fissile production rate increases with increasing Th fraction.

Table 2. One-Dimensional ALICE Results

	Th Vol %				
	2	6	13	20	30
T6					
Fall	0.282	0.264	0.264	0.305	0.363
Blanket	0.577	0.574	0.572	0.546	0.516
T7					
Fall	0.168	0.161	0.171	0.170	0.163
Blanket	0.048	0.047	0.048	0.047	0.043
T	1.075	1.046	1.055	1.068	1.085
Fe(n,γ)	0.394	0.156	0.031	0.014	0.008
Th(n,γ)	0.969	1.504	1.339	1.283	1.233
U(n,γ)	0.018	0.028	0.021	0.018	0.017
Th(n,f)	0.005	0.013	0.029	0.040	0.057
U(n,f)	0.168	0.231	0.141	0.113	0.078
F	0.783	1.245	1.177	1.152	1.138
E_n, MeV	54.3	67.0	51.9	48.0	44.3
M_f	3.28	4.01	3.15	2.93	2.72

T6 = ^{6}Li(n,T)α reactions per DT neutron

T7 = ^{7}Li(n,n'T)α reactions per DT neutron

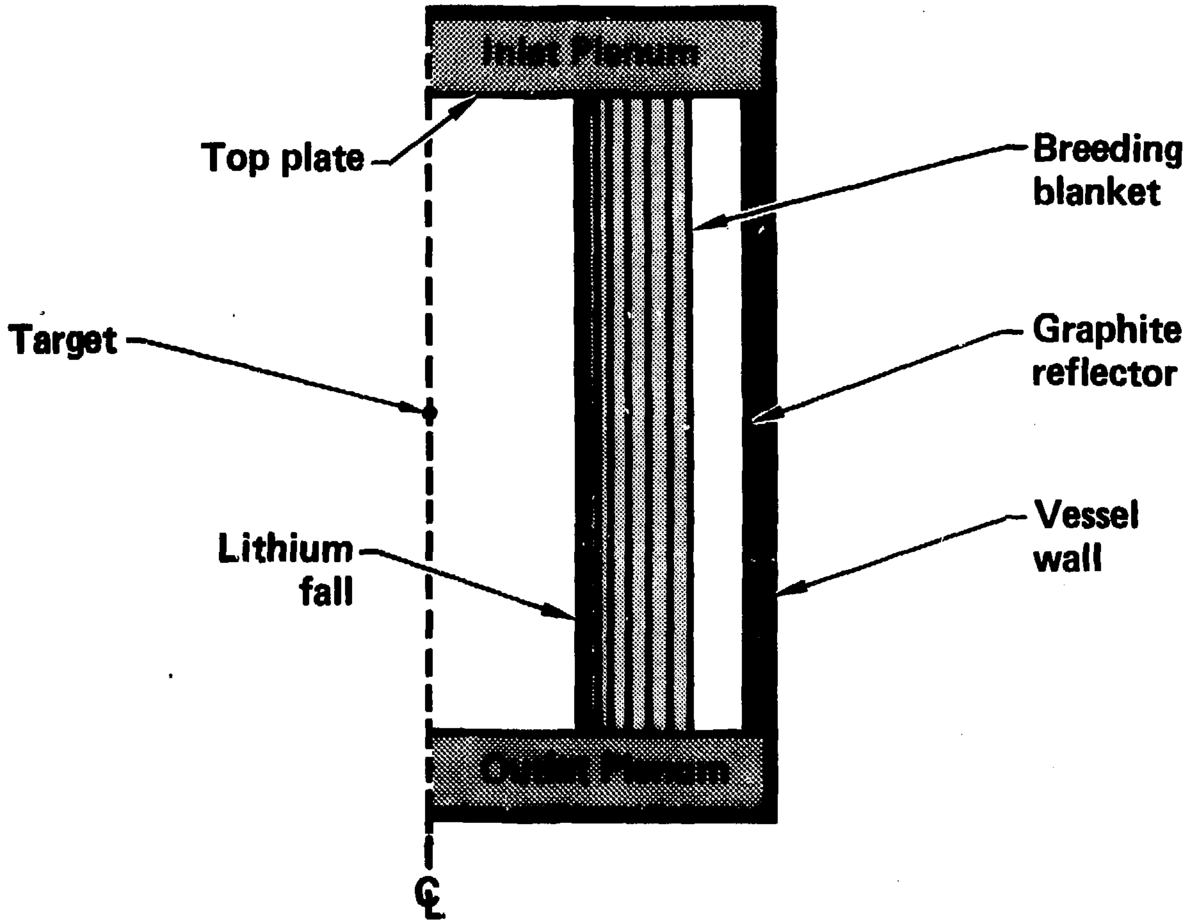

Fig. 6 Two-dimensional neutronics model.

Table 3. Material Compositions

Zone	Material	Density g/cm^3	Isotope	Atom Fraction %
Target	DT	100	D	50.0
			T	50.0
Lithium Fall Inlet Plenum Outlet Plenum	Li	0.50	^{6}Li	5.0
			^{7}Li	95.0
Graphite Reflector	C	1.70	^{12}C	100.0
Vessel Walls & Top Plate	Fe	7.86	Nat Fe	100.0
Breeding Blanket*	Li	0.50	^{6}Li	0.547
			^{7}Li	10.383
	Be	1.85	^{9}Be	75.384
	Fe	7.86	Nat Fe	2.153
	HM**	11.66	^{232}Th	11.476
			^{233}U	0.058

*The combination of 20 vol% Li, 48 vol% Be, 2 vol% Fe and 30 vol% Th gives a material density of 4.64g/cm^3. The density in the zone was 2.32 g/cm^3 to account for the 50% packing fraction.

** HM - Heavy Metal

The results are tabulated in Tables 4 and 5. The tritium breeding ratio is 1.08, and the net fissile breeding ratio is 0.97 for a T + F of 2.05. The total number of fissions per DT neutron is 0.122 with Th contributing 0.046 and U giving 0.076. The neutron energy deposited is 41.1 MeV which gives a *fusion energy multiplication* factor of 2.53.

The breakdown in tritium breeding is as follows.

lithium fall	0.43
breeding blanket	0.36
lithium plenums	0.29
	1.08

The cumulative F as a function of position in the breeding blanket is shown in Fig. 7. About 85% of the fissile breeding occurs in the inner half of the blanket. As a result, the enrichment rate at the inner edge of the blanket is a factor of three higher than the average for the blanket as shown in Fig. 8.

The heavy metal inventory of this blanket is ~300 MT. With F ~1 and a fusion power of 800 MW, the discharge enrichment after one full power year is 1.0%. AFter the decay of all the ^{233}Pa the final enrichment is 1.13%.

A fuel management scheme may be desirable in order to level out the fissile concentration across the breeding blanket. One scheme, which would eliminate the need for removing fuel from the reactor and repositioning it, is to rotate the fuel continuously from the inside to the outside of the blanket. This is illustrated in Fig. 9. A group of 7 Be columns forms a single rotating array. There are 10 such arrays. The seven columns are attached to a disk at the top and bottom of the chamber. These disks rotate slowly bringing the outer blocks toward the inside and vice versa. The regions between the rotating disks have columns in fixed positions.

Table 4. Tritium Breeding by Zone and Isotope

Zone	T6	T7	T
Lithium Fall	0.263	0.171	0.434
Breeding Blanket			
1*	0.060	0.015	0.075
2	0.065	0.007	0.072
3	0.105	0.007	0.112
4	0.058	0.002	0.060
5	0.025	0.001	0.026
6	0.012	---	0.012
Top Plenum	0.101	0.027	0.128
Bottom Plenum	0.123	0.038	0.161
Total	0.812	0.268	1.080

* Breeding blanket zones 1-6 from inner to outer.

Table 5. Capture and Fission by Zone and Element

Breeding Blanket Zone*	Th(n,γ)	Th(n,f)	U(n,γ)	U(n,f)	Fe(n,γ)
1	0.256	0.019	0.002	0.015	0.002
2	0.249	0.012	0.002	0.017	0.002
3	0.327	0.011	0.004	0.025	0.002
4	0.146	0.003	0.002	0.012	
5	0.058	0.001	0.001	0.005	---
6	0.020	---	---	0.002	0.002
Total	1.056	0.046	0.011	0.076	0.009

* Zones 1-6 from inner to outer

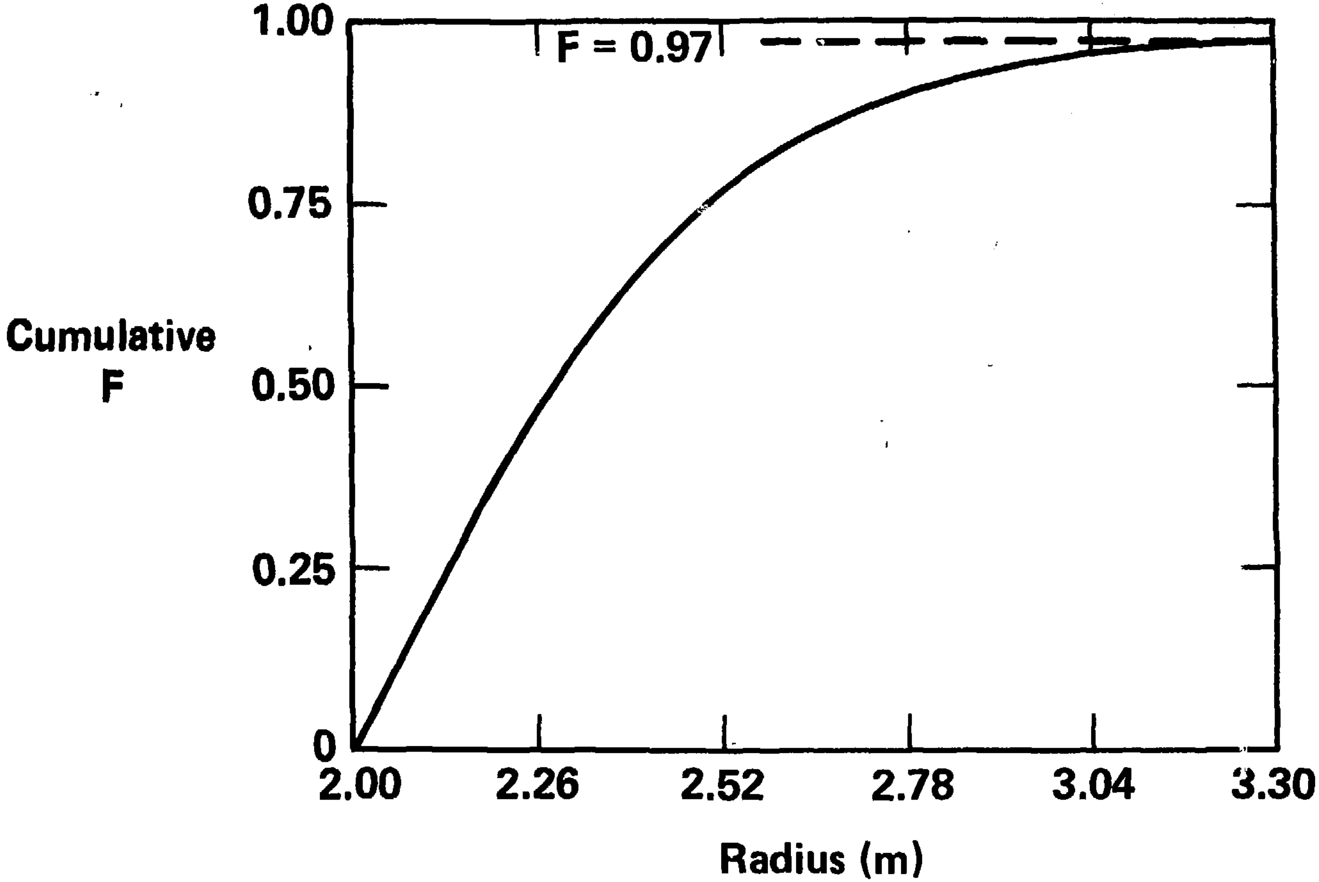

Fig. 7 85% of the fissile breeding occurs in the inner half of the blanket.

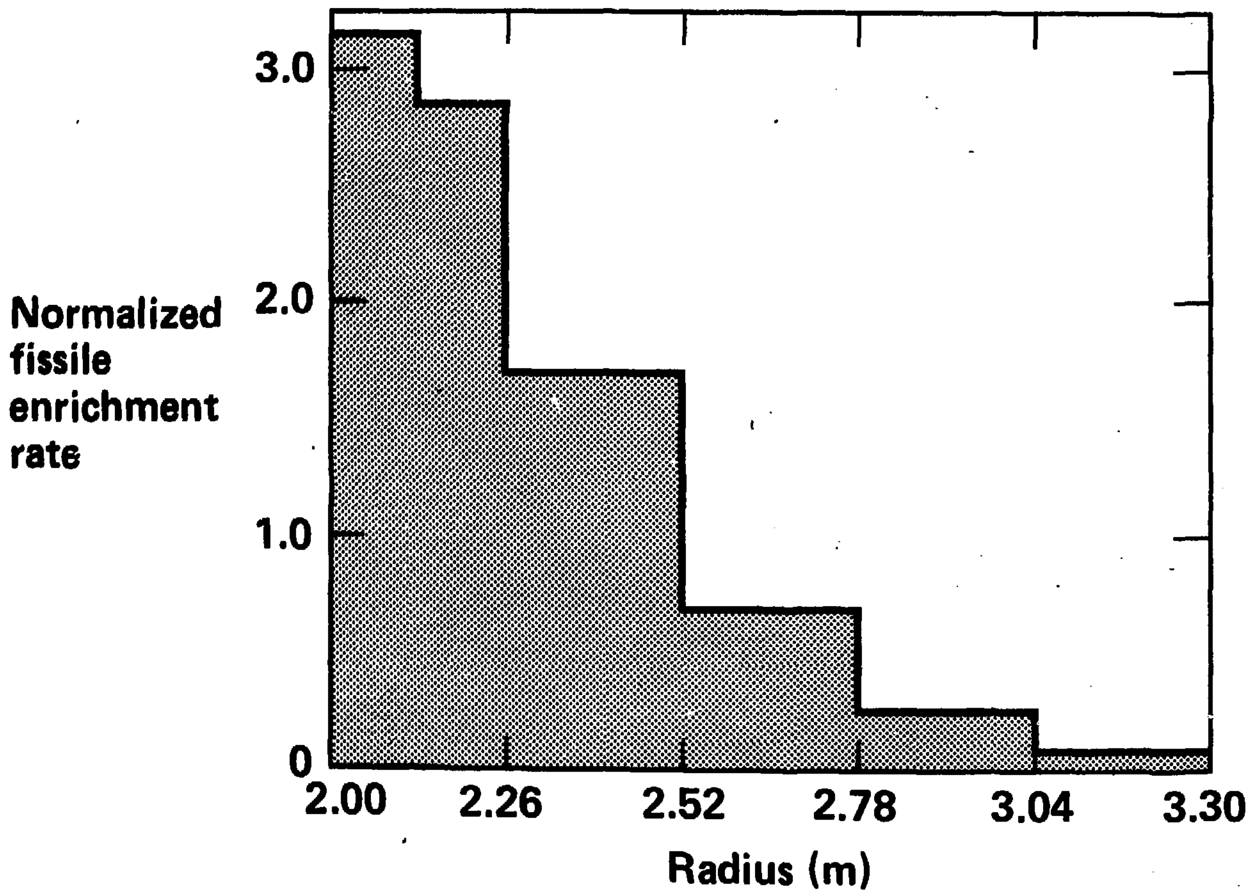

Fig. 8 Fissile enrichment at blanket inner edge is 3 times higher than the energy.

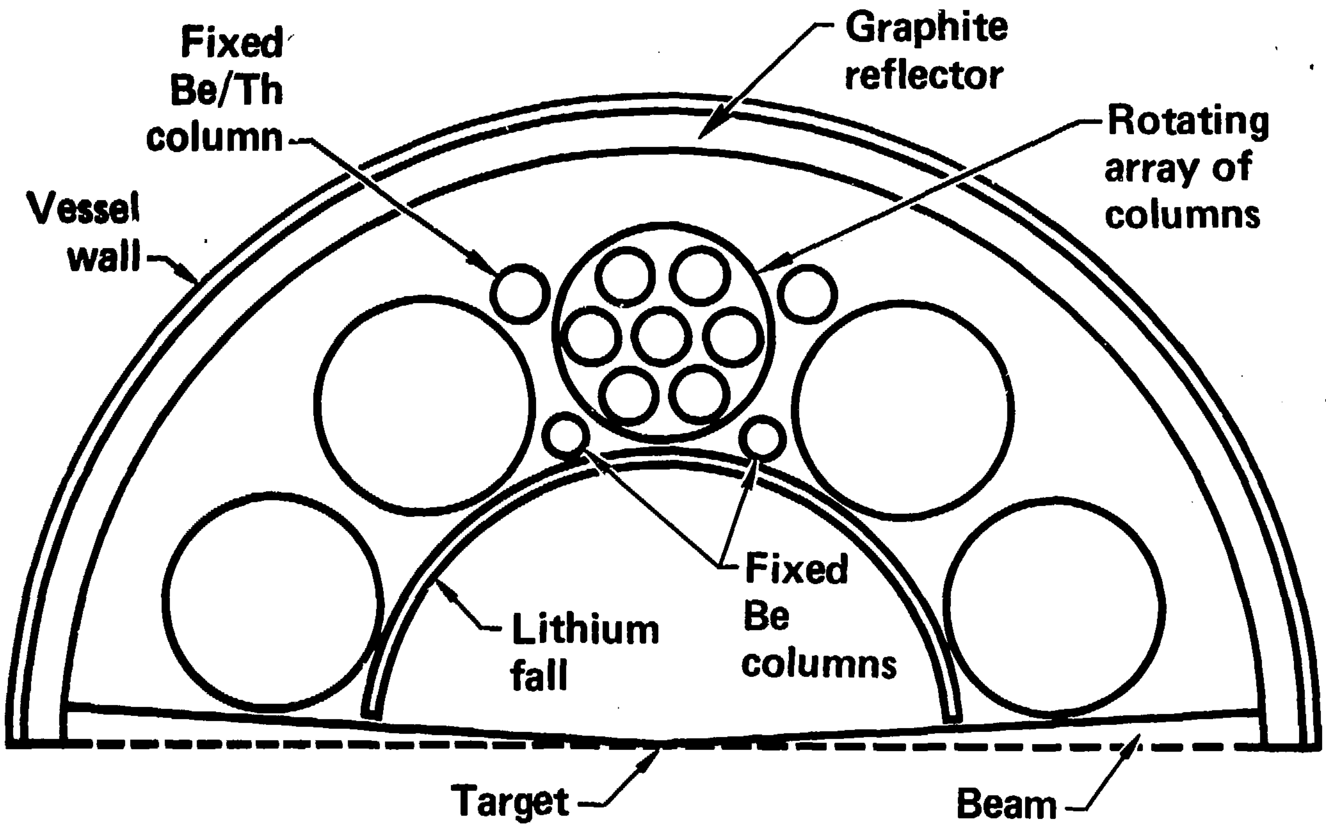

Fig. 9 One scheme to make the fissile enrichment more uniform across the blanket.

Two additional calculations were carried out to determine the variation as the fissile content increased from 0 to the discharge enrichment of 1%. Figure 10 shows that T and F are essentially constant over the life cycle. The total fission rate increases from 0.045 to 0.20 as the ^{233}U enrichment increases from 0 to 1.0%. As a result, the fusion energy multiplication factor increases from 1.7 to 3.3. If the fusion power were held constant at 800 MW, the thermal power would increase from 1360 MW_t to 2640 MW_t over the one-year enrichment period.

Resonance Self-Shielding

As previously noted, we found significant differences between results obtained with TART and ALICE. ALICE has been shown to give more accurate results when resonance absorption is a feature of the cross sections. This is the case for Th(n,γ), ^{233}U(n,f), ^{233}U(n,γ) and Fe(n,γ) reactions.

Table 6 compares the results of TART and ALICE for the reference 2-D case. TART gives lower values for ^6Li(n,T)α, Fe(n,γ) and U(n,f). It gives higher values for Th(n,γ) and U(n,γ). As a result, TART predicts a tritium breeding ratio less than 1.0 and a significantly smaller neutron energy deposition. To get $T > 1.0$ with TART would require a higher ^6Li concentration. This would further reduce the U(n,f) rate and give an even lower value of M_f.

Table 7 gives another comparison of TART and ALICE. In this case, the breeding blanket was 10 vol% Th (0.5% ^{233}U), 19 vol% Li, 3 vol% Fe, and 68 vol% Be. The ^6Li fraction of 4.4% was chosen to give $T \sim 1$ with TART. As in the previous case, ALICE shows significantly higher ^6Li(n,T)α and ^{233}U(n,f) rates, and a lower Th(n,γ) reaction rate.

From the standpoint of a suppressed-fission hybrid, results obtained with TART make this particular blanket concept look more attractive than it really is (i.e., TART underestimates the fission rate). The degree of discrepancy with other hybrid blanket concepts cannot be predicted a priori.

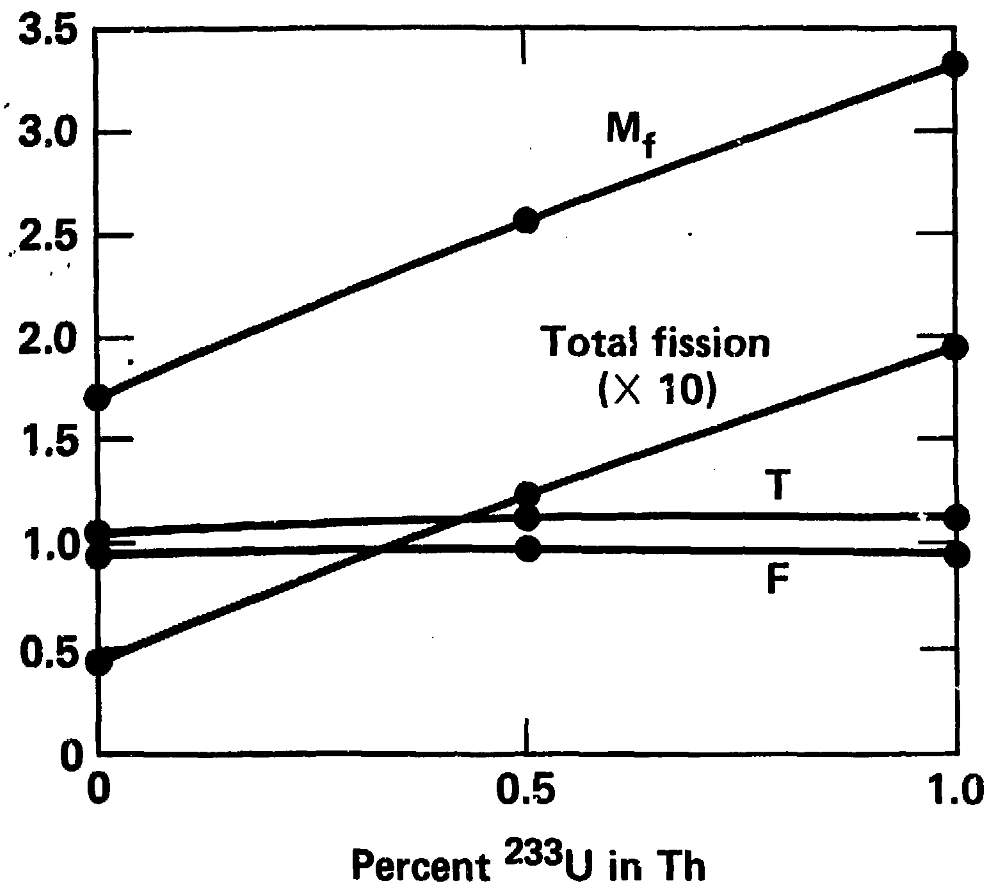

Fig. 10 Breeding remains constant but energy multiplication increases as U-233 concentration increases.

Table 6. Comparison of ALICE and TART Results for Reference Case

Parameter	ALICE	TART
T_6	0.812	0.526
T_7	0.268	0.275
T	1.080	0.801
Th(n,γ)	1.056	1.285
U(n,γ)	0.011	0.038
Fe(n,γ)	0.009	0.004
Th(n,f)	0.046	0.046
U(n,f)	0.076	0.034
Fissions	0.122	0.080
E_n	41.1 MeV	33.2 MeV
M_f	2.53	2.09

Table 7. Comparison of ALICE and TART Results for blanket with 10 vol% Th, T ~1 with TART

Parameter	ALICE	TART
T_6	1.143	0.832
T_7	0.283	0.281
T	1.426	1.113
Th(n,γ)	0.685	0.978
U(n,γ)	0.007	0.004
Fe(n,γ)	0.017	0.012
Th(n,f)	0.016	0.016
U(n,f)	0.046	0.030
Fissions	0.072	0.046
E_n	30.7	27.2
M_f	1.94	1.77

Summary

An ICF hybrid that uses a Be neutron multiplier, Th metal fuel and Li coolant has been described. It is found that increasing the Th content to 30 vol% actually reduces the energy multiplication factor. The ^{6}Li enrichment required to achieve a tritium breeding ratio of one increases with increasing fertile fuel fraction. At high enrichments, the ^{6}Li effectively competes for neutrons and reduces parasitic capture in Fe and fission in the bred fissile fuel. The large heavy metal inventory also permits a fuel residence time on the order of one year for the system described here. Another important conclusion is that resonance self-shielding effects are important and it is recommended that ALICE be used instead of TART for hybrid calculations.

Acknowledgements

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