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FUSION BLANKETS FOR HIGH-EFFICIENCY POWER CYCLES[*+]

MASTER

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Summary

The efficiencies of blankets for fusion reactors are usually in the range of 30 to 40%, limited by the operating temperatures (500°C) of conventional structural materials such as stainless steels. In this project "two-zone" blankets are proposed; these blankets consist of a low-temperature shell surrounding a high-temperature interior zone. A survey of nucleonics and thermal hydraulic parameters has led to a reference blanket design consisting of a water-cooled stainless steel shell around a BeO, ZrO_2 interior (cooled by Ar) utilizing Li_2O for tritium breeding. In this design, ~60% of the fusion energy is deposited in the high-temperature interior. The maximum Ar temperature is 2230°C leading to an overall efficiency estimate of 55 to 60% for this reference case.

Introduction

The overall intent of this research is to design a near-term fusion power plant with a high-efficiency power cycle. In order to achieve high efficiency in a thermal power plant, high-coolant temperatures are necessary; in general, the higher the temperature available, the higher the efficiency of the cycle. The operating temperatures of conventional structural materials such as austenitic or ferritic steels are limited to ~500°C which corresponds to a maximum cycle efficiency of ~40%. Higher coolant temperatures are attainable utilizing either of the following approaches: (1) structural material with higher temperature capability (e.g., refractory metal like molybdenum (TZM) or niobium) can be used; (2) the blanket can be designed to be a "two-temperature-zone" blanket in which the first wall and structural material operate at a much lower temperature than the bulk of the blanket. The former approach requires either a liquid metal (or vapor) coolant or an inert gas coolant. Structural strength considerations limit the maximum temperature to 800° to 1000°C, depending on choice of coolant and blanket design. In the two-temperature approach, first proposed by BNL[1] for minimum activity blankets, the high-energy neutrons (14 MeV) from the DT reaction penetrate deeply and deposit their energy over the volume of the blanket, rather than on the first wall. If a thermally insulating layer is placed between the hot interior and the cooler structural shell of the blanket module, heat can be extracted at two different temperature levels by separate coolant streams for the interior and structural shell.

In general, the temperature available in the coolant from the hot interior will be limited by the corrosion/erosion behavior of the interior material in the coolant and not by structural stress considerations. With inert gas coolants (e.g., He or Ar) and refractory interiors (e.g., graphite, oxides, or carbides), it appears possible to achieve coolant temperatures up to 2500°C. With more reactive coolants (e.g., steam or potassium vapor) accompanied by the use of a refractory metal structure, maximum coolant temperatures will be somewhat lower, though they can still be very high. For example, materials experiments with steam coolant have been carried out at BNL as part of a development program of high-temperature blankets for synfuel applications,[2] and indicate that coolant temperatures of at least 1500°C are practical using either ZrO_2 or Al_2O_3. In fact, higher operating temperatures may be possible with yttria-stabilized ZrO_2, judging from tests on this material in high-temperature wind tunnels.

The mode of tritium breeding will also affect the temperature capability of two-zone blankets. The temperature capabilities discussed above assume that there is no tritium breeding in the hot interior of the blanket (though breeding could be carried out in the low-temperature shell). If tritium breeding takes place in the hot interior, allowable coolant temperatures will be significantly reduced.

There appear to be two approaches to breeding tritium in the hot interior—solid lithium compounds and liquid lithium in refractory metal tubes. In the first approach, high melting point solid lithium compounds (e.g., Li_2O or $LiAlO_2$) can be used in the module interior; the bred tritium

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would be released to the high-temperature coolant stream, with subsequent recovery and recycle to the plasma. However, in order to ensure adequate tritium release capability, it is necessary to maintain small particle size in the solid lithium compound and to prevent sintering. Tests at BNL[3] have investigated the tritium release characteristics of solid lithium compounds at elevated temperatures (up to 1000°C) for extended periods of time (up to three months). Lithium oxide and $LiAlO_2$ appear suitable for use to at least 1000°C and possibly higher. It is doubtful, however, that substantially higher operating temperatures can be achieved, since at 1000°C the materials are entering the range ($\sim 0.6\ T_m$) where sintering effects become important.

Thus tritium breeding in the hot interior appears to limit maximum coolant temperatures to ~1000°C, assuming inert gas coolant. Tritium breeding with a reactive coolant such as steam is probably not feasible because of the chemical reaction between steam and solid lithium compounds and the difficulty of isotopically separating tritium from hydrogen in steam.

The two-temperature-zone blanket approach can be used with a hot interior of liquid lithium in refractory metal tubes (with a thermal insulator between the hot interior and the cooler metal shell). The interior would then be cooled either by an inert gas or potassium coolant. Tritium would be extracted either by circulating the lithium to an external processing unit or by releasing it to the coolant stream with subsequent trapping. Compatibility and structural considerations appear to limit maximum coolant temperatures to about 1200°C with liquid lithium interiors.

A survey analysis of several variations of the above combinations of materials, coolants and breeding options have been performed.[4] Neutronics and photonics analyses along with thermal hydraulic analysis lead to two favorable conclusions regarding two-zone blankets with solid tritium breeding compounds in the hot interior: (1) two-temperature-zone blankets can be designed with a high (60 to 70%) efficiency for deposition of fusion energy in the hot interior, and (2) blankets with solid lithium compounds in the hot interior can achieve tritium breeding ratios of ~1.5 if suitable neutron multipliers are used. These favorable characteristics led to the selection of a blanket of this type as a starting point in the detailed design study which follows.

Design Selection

For the purpose of this design study, an ETF-sized plasma is presumed.[5] The major radius of the Tokamak is 5.6 m. The plasma has a D-shaped cross section with a half-width of 1.34 m and elongation of 1.6 to 1.0. Impurities are controlled by means of a bundle divertor which has a 10-cm scrape-off layer. The divertor is assumed to be ~30% efficient in terms of total alpha particle power absorbed. The plasma thermal power is 1080 MW, which leads to a neutron wall loading of 2.1 MW/m^2.

The previous study[4] mentioned above aided in the selection of blanket composition and layout. Figure 1 illustrates the blanket layout which was utilized for nucleonics (neutronics and photonics) and thermal hydraulics analyses. In a manner of speaking, this schematic represents a "three-zone" blanket: (1) low-temperature first wall and structure, (2) high-temperature blanket and neutron multiplier, and (3) intermediate-temperature breeding blanket. It is the detailed composition of these three zones which will constitute the reference high-efficiency blanket design. The first wall consists of water-cooled stainless steel (SS 316) tubes; this first wall is 1.5 cm thick and has approximately 70% steel and 30% water. The first wall is followed by a 2-cm-thick "mop up" breeding zone composed of liquid ^6Li mixed with lead bismuth with varying volume fractions of these components. The first wall and mop-up zones are thermally insulated from both the high-temperature blanket and breeding blanket by a 1-cm-thick insulator of BeO or ZrO_2 with a volume fraction of 20%. The high-temperature blanket is 20 to 50 cm thick and has various options for composition. The use of BeO, ZrO_2, and Zr either singularly or in combination with each other has been considered. This region is cooled by high pressure Ar gas which flows vertically through this region with 20% voidage. The high-temperature blanket is insulated from the breeding blanket by a 1-cm-thick insulator of the same composition as mentioned previously. The breeding blanket is composed of porous INCONEL tubes containing Li_2O and rods of ZrO_2. This region is 30 cm thick and is cooled by Ar. This coolant flows in two separate streams, one through the center of the Li_2O and the second upward through the thermal insulator to cool the high-temperature blanket. The overall height of these modules is 55.5 to 60.5 cm, while the width is 43 cm. Three of these modules will fit side-by-side on a larger blanket segment backed by a shield of SS316, B_4C, and water. The thickness of this shield will be 70 to 90 cm depending on space limitations on the inboard side of the torus.

Nucleonics and thermal hydraulics have been surveyed for a variety of cases. Cases were examined to determine the effects of thickness and composition of the high-temperature blanket; materials used were BeO, ZrO_2, and Zr in 10, 20, and 30 cm thicknesses. Due to insufficient tritium breeding ratios in the earlier cases examined, survey was also made to determine the effect of increasing the volume fraction of lithium in the mop-up breeding zone from near zero to 8%. In all cases investigated, the make up of the main breeding blanket was Li_2O (50% enriched) with a volume fraction of .20, ZrO_2 with a volume fraction of .50, the porous INCONEL tubes with a volume fraction of .10, and the remainder of the zone was voidage (Ar coolant). A constant thickness of

1.5 cm for the first wall and a thickness of 1.0 cm for the thermal insulators were maintained throughout all the cases examined. Values of Q (the energy released in plasma and blanket per fusion event) and BR (the tritium breeding ratio) are shown in Table 1, as functions of high-temperature blanket composition and thickness and lithium volume fraction in the mop-up zone.

The cases chosen for the reference design and an alternate backup case are indicated on Table 1. The dramatic increase in breeding ratio is shown clearly in all cases but perhaps is most evident in the reference case where the improvement is a factor of 70% via the addition of the mop-up breeding zone containing 8% ^{6}Li. This increase in breeding ratio takes place with an accompanying drop in Q value (due to the absorption of neutrons closer to the first wall) of only 8%. Subtracting the plasma fusion energy of 17.6 MeV enables the determination of drop in blanket Q value. This drop turns out to be 30% which must again be weighed against the overall increase of 70% in breeding ratio, which is a most equitable exchange. The backup case exhibits a lower breeding ratio and Q value. A mechanism whereby this lower breeding ratio can be counterbalanced will be discussed in the next Section.

In addition to breeding ratio and Q value, blanket heating rates, fractions of energy deposited in the blanket interior and thermal hydraulics parameters were also surveyed to aid in the selection of the reference and backup cases which are defined in the following Section.

Reference and Backup Designs

Figure 2 illustrates the detailed module configuration for both the reference and backup designs. The reference design has a high-temperature zone thickness of 20 cm of BeO rods (1 cm diameter); the zone is approximately 20% voids. The main breeding zone, which is 30 cm thick, also contains rods, this time they are ZrO_2 with 1 cm diameter, also present are porous INCONEL tubes filled with Li_2O. This zone is also approximately 20% voids. The mop-up breeding zone is composed of 40% Pb-Bi and 8% liquid ^{6}Li and is the same for both the reference and backup designs. The backup design has a high-temperature zone (composed of 1-cm-diameter Zr rods) which is 30 cm thick. The main breeding zone in the backup design is the same as the reference case.

Figure 3 illustrates the backup configuration in isometric view. Three of these modules will be placed side-by-side and then mounted on a shield plate to form a blanket segment.

Table 2 illustrates the fractions of energy (Q) absorbed in each of the module zones for the reference and backup cases. In both cases, the total fraction of energy absorbed in the hot interior (zones 6, 7, and 9) approach 60%. Note that for both cases very small energy amounts penetrate to the shield. The fraction f_1/f_2 illustrates quite clearly one of the reasons for the selection of the reference case: twice as much energy is absorbed in the high-temperature blanket as in the main breeding zone. This larger fraction of high-temperature heat will convert more efficiently to electricity than in the backup case. These energy absorption fractions are closely related to the neutron fluxes illustrated in Figs. 4 and 5. Figure 4 shows the total and 14-MeV fluxes for the reference case while Fig. 5 depicts the same fluxes for the backup case. The calculation of these fluxes was detailed in a previous report.[4] The efficiency of energy absorption in the high-temperature blanket of the reference case is indicated by the fall-off of the 14-MeV flux by a factor of 40 in this zone. The 14-MeV flux falls off by only a factor of 6 over the high-temperature zone in the backup case. Two-dimensional neutronics calculations performed previously[6] indicate that there will be only a slight reduction of the 60% energy absorption factors determined in the one-dimensional analysis performed here.

The next step in the design analysis was the determination of neutronic and photonic (gamma) heating profiles shown in Figs. 6 and 7 for the reference and backup cases, respectively. The reference case, shown in Fig. 5, depicts for the most part an easy to handle heating profile, the 2 to 3 W/cm^3 average across the high-temperature zone is removed with a peak Ar temperature of 2230°C. The sharp heating rate increase near the front of the main breeding zone is cause for some concern and a solution to this sharp profile in both the high-temperature and breeding zones of the backup design heating rates will also require similar attention. The heating rates identified here led to the parameters listed in Tables 3 and 4. Table 3 shows the calculated blanket temperatures for the first wall and structure as well as the high-temperature and breeding zones. The peak temperature of 2230°C in the high-temperature zone should prove an excellent aid in increasing power cycle efficiency. The outlet temperature of 900°C in the breeding zone should create no problems with Li_2O melting or tritium extraction. Tritium removal will be accomplished basically through the secondary Ar coolant stream flowing through the center of the INCONEL-encased Li_2O in a manner similar to that proposed in the STARFIRE design.[7] Pressure drops are indicated in Table 4 on a per module basis. Once again, these data indicate that both the designs are problem-free in this area.

The question of heat removal in the sharply-peaked front edge of the main breeding zone indicated on Figure 6 is addressed in the following manner: Li_2O (the principle neutron absorber and, hence, heat generator) is varied in concentration throughout the main breeding zone. Figure 8 lists these Li_2O fractions along with breeding ratios in specific regions of the main breeding zone. Regions 9 to 12 are 1 cm thick while region 13 is

26 cm thick maintaining the 30 cm thickness of the main breeding zone. Figure 8 also shows the thermal neutron flux across the breeding zone. It is these thermal neutrons which account for the vast majority of breeding reactions. This stepping of Li_2O concentration reduces the overall breeding ratio by about 3%, while alleviating the problems caused by sharp peaks in the heating rates.

The low breeding ratio (0.93) in the backup case presents somewhat of a problem. It would be necessary to utilize a superbreeding blanket (BR≈1.6) for 25% of the total blanket around the reactor if the backup concept were to be part of a viable reactor concept. The design of this superbreeding blanket is currently under way as part of a synthetic fuel investigation at BNL.

Three blanket modules are placed side-by-side on a shield/backing plate to form blanket segments. These segments then surround the minor circumference of the torus, as shown in Fig. 9. The segments are 1.4 m deep by 1.3 m wide and the length of the segments varies from 1.5 m inboard to 3.0 m outboard of the plasma. Figure 10 depicts these length variations by showing a top view of the reference design. This arrangement of segments is analogous to that proposed for the STARFIRE design.[7] Each segment will be self-contained in coolant headering for both water and Ar. The primary Ar circuit (p=30 atm) will have Ar channeled into the bottom of the segments and will then flow upward penetrating the thermal insulation between the breeding zone and the high-temperature zone and will be channeled out at the apex of the high-temperature zone, as illustrated in Fig. 3. The secondary Ar flow (maintained at less than 30 atm) will be through the Li_2O tube centers into tube heads and flow will be along the length of the segments.

Conclusions

The blankets designed in this report exhibit several of the features of the STARFIRE design while sized to the smaller ETF reactor. When coupled with high-efficiency power conversion cycles, efficiencies of 50 to 60% are attainable. These efficiencies represent as much as a 100% increase over STARFIRE and other more traditional fusion reactor designs.

Preliminary costing studies indicate that most of this efficiency improvement will be reflected as savings in capital costs of this fusion reactor. A reasonable expectation for similar savings in electricity costs is also indicated.

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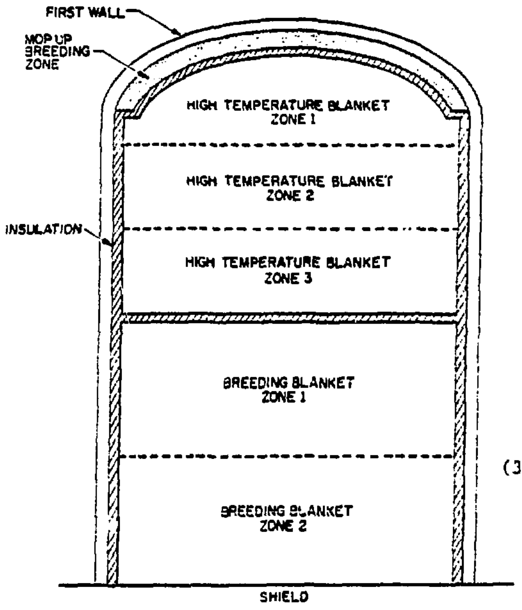

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Fig. 1. Blanket schematic for computer analysis.

TABLE 1 Tritium Breeding Ratios and Q Values

High-temperature-zone composition		Mop-up breeding zone volume fractions: ^{6}Li .001, Pb .001 — BR	^{6}Li .001, Pb .001 — Q (MeV)	^{6}Li .02, Pb .10 — BR	^{6}Li .02, Pb .10 — Q (MeV)	^{6}Li .08, Pb .40 — BR	^{6}Li .08, Pb .40 — Q (MeV)
BeO ZrO_2	10 cm 20 cm	0.43	23.92	0.76	22.51	0.90	22.14
BeO ZrO_2	20 cm 10 cm	0.42	24.58	0.78	22.94	0.92	22.47
BeO	20 cm (Reference)	0.65	23.59	0.97	22.16	1.10	21.77
BeO	30 cm	0.41	24.86	0.79	3.10	0.93	22.61
ZrO_2	20 cm	0.60	21.50	0.77	20.90	0.88	20.83
ZrO_2	30 cm	0.41	22.30	0.64	21.44	0.78	21.29
Zr	20 cm	-	-	0.84	20.57	0.91	20.53
Zr	30 cm (Backup)	-	-	0.85	21.03	0.93	20.92

TABLE 2 Fractions of Energy Absorbed

Zone	Reference design	Backup design	
3. First wall	.17	.18	
4. Mopup breeding	.24	.18	
5. Insulation	.01	.00	
6. High temperature and	.25	.09	$= f_1$
7. Multiplier	.14	.19	
8. Insulation	.00	.00	
9. Main breeding	.18	.30	$= f_2$
10. Shield	.00	.06	
f_1/f_2	2.17	0.93	
Q	21.77 (MeV)	20.92 (MeV)	

TABLE 3 Coolant Pressure Drops

	Reference	Backup
Water		
Inlet manifold	2.48 psi	1.11 psi
Cooling tubes	0.78	0.35
Outlet manifold	3.77	1.68
3 meters of piping	11.30	5.04
Argon		
Breeding zone	0.07 psi	0.03 psi
High-temperature zone	0.08	0.10
3 meter outlet plenum	0.50	0.31
3 meter duct	0.70	0.44

TABLE 4 Temperatures in Blanket

	Reference °C	Backup °C
Water (wall coolant)		
p = 1800 psia		
Inlet	100	100
Outlet	327	327
Argon (blanket coolant)		
p = 30 atm Breeding zone		
Inlet	292	48
Outlet	897	965
High temperature zone		
Inlet	897	965
Outlet	2227	2227

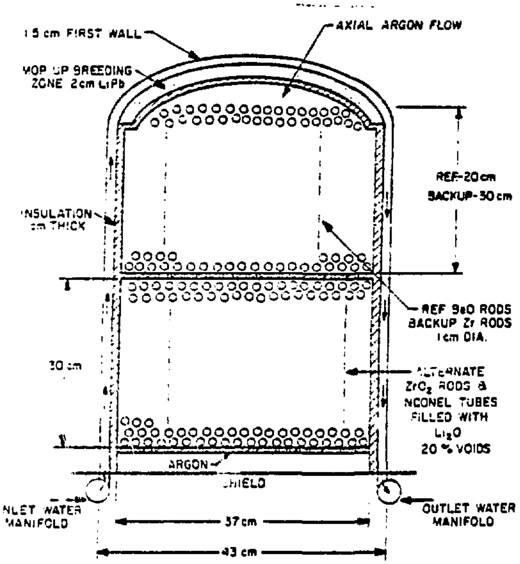

Fig. 2. Blanket module design. (6-546-80)

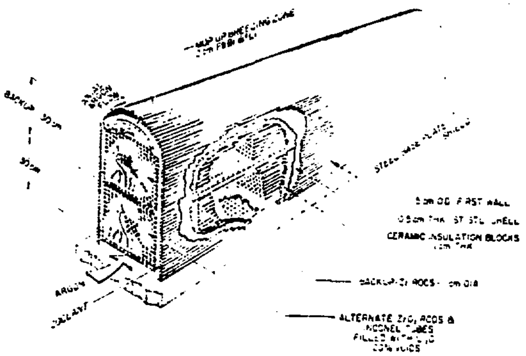

Fig. 3. Back-up design - isometric view. (8-679-80)

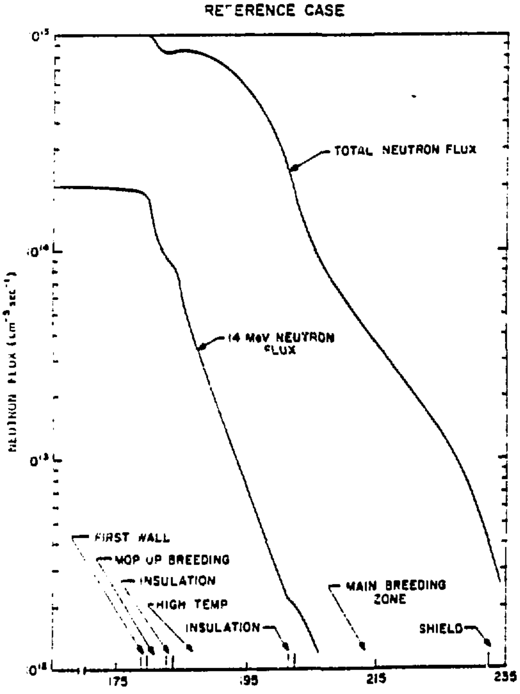

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Fig. 4. Neutron fluxes - reference design.

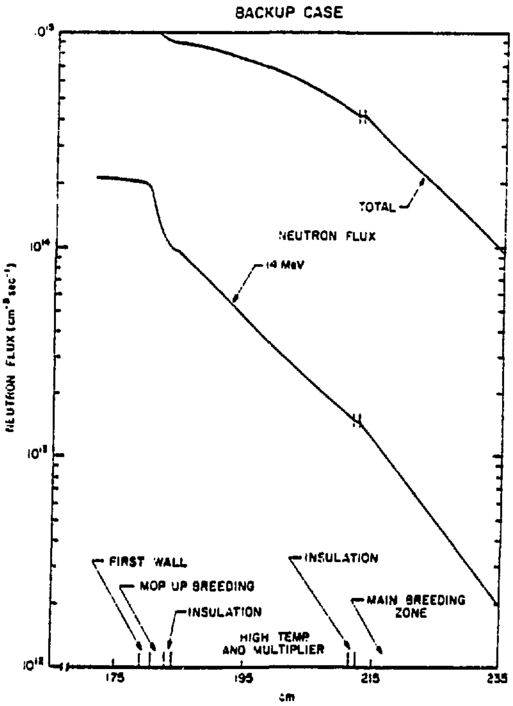

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Fig. 5. Neutron fluxes - back-up design.

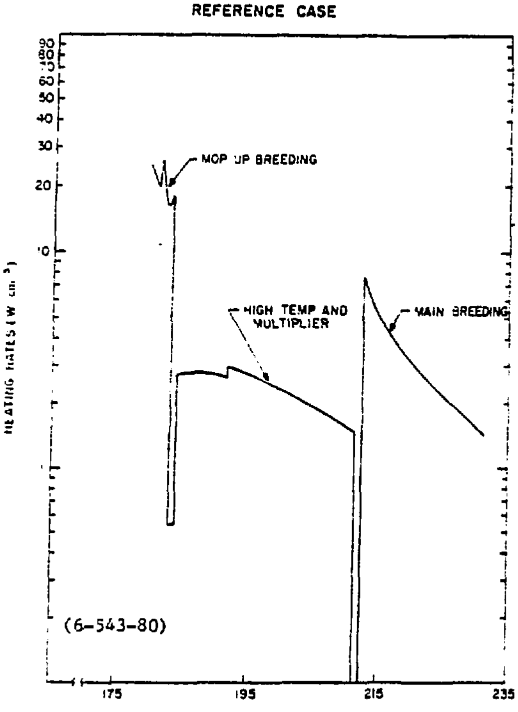

Fig. 6. Heat deposition - reference design.

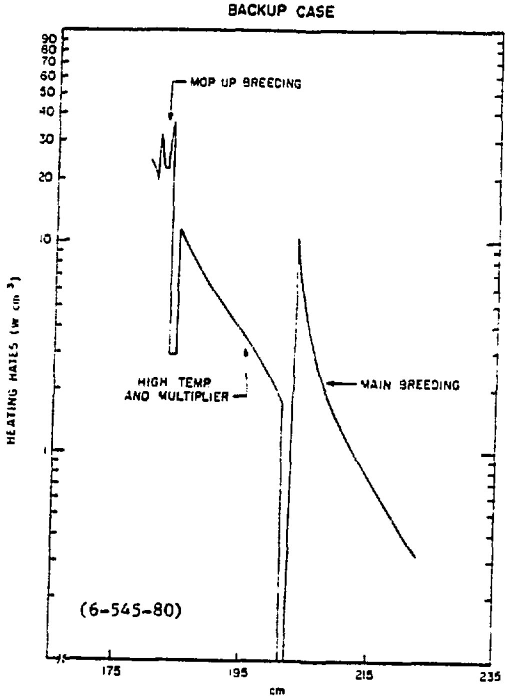

Fig. 7. Heat deposition - back-up design.

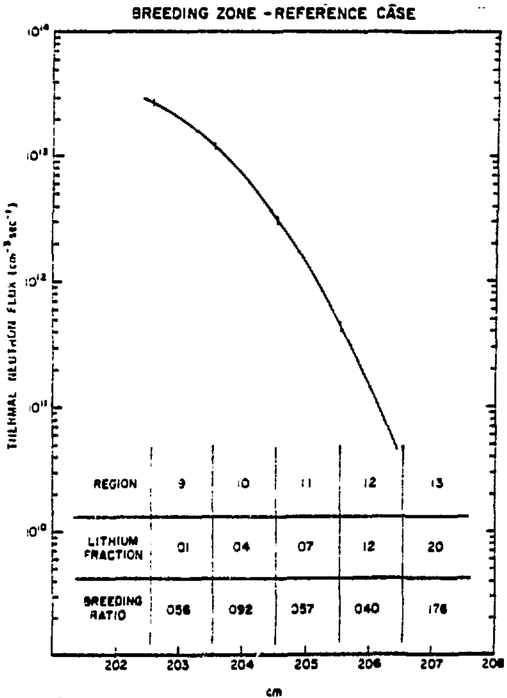

Fig. 8. Thermal neutron flux - breeding zone.
(6-544-80)

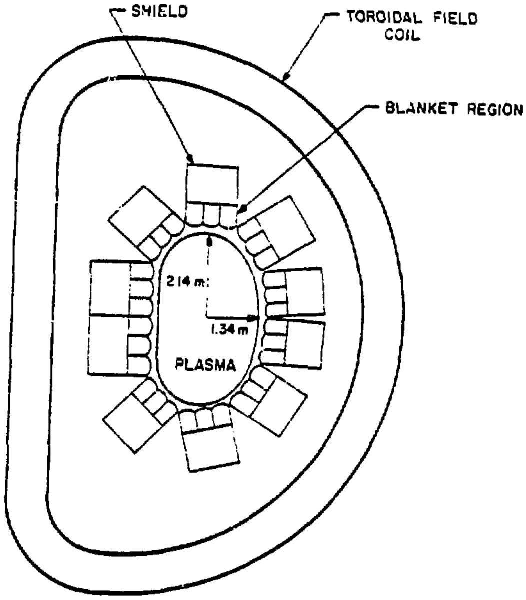

Fig. 9. Blanket cross section - side view.
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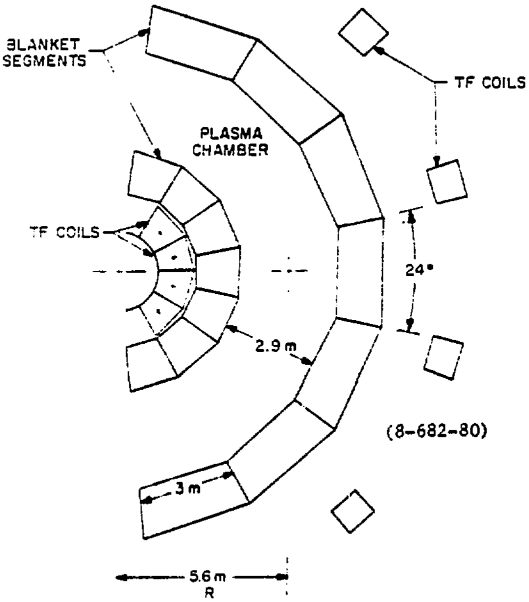

Fig. 10. Blanket cross section - top view.