A compact Tokamak transmutation reactor*

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Abstract The low aspect ratio Tokamak is proposed for the driver of a transmutation reactor. The main parameters of the reactor core, neutronic analysis of the blanket are given. The neutron wall loading can be lowered from the magnitude order of 1 MW/m^2 to 0.5 MW/m^2 which is much easier to reach in the near future, and the transmutation efficiency (fission/absorption ratio) is raised further. The blanket power density is about 200 MW/m^3 which is not difficult to deal with. The key components such as diverter and center conductor post are also designed and compared with conventional Tokamak. Finally, by comparison with the other drivers such as FBR, PWR and accelerator, it can be anticipated that the low aspect ratio transmutation reactor would be one way of fusion energy applications in the near future.

Keywords Fusion-fission hybrid reactor, Compact Tokamak, Transmutation

1 Introduction

Relative to previous fusion-fission hybrid reactor[1~3], our new concepts are based upon a small D+T fueled Tokamak device (conventional or low aspect ratio Tokamak) serving as strong neutron source in fusion power as little as 10~100 MW to drive a high level waste (HLW) transmutation power plant.

The new blanket-concept relies on the intense neutron flux to achieve a multiplicable factor of blanket energy (M) as high as 10~100, $M=[E_{\text{fission}}/E_{\text{fusion}}]\cdot[K_{\text{eff}}/\nu(1-K_{\text{eff}})]$, where K_{eff} is the critical factor, ν the mean number of neutron in fission process (~3), E_{fission} the energy released per fission (~200 MeV), E_{fusion} the energy released per D+T fusion (~14 MeV). When maintaining subcriticality K_{eff} of up to 0.95, the intense thermal neutron flux ($>5\times 10^{15}\text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$) in the blanket ensures adequate neutron economy.

The previous analysis showed that the neutron wall loading can be lowered to the magnitude order of 1 MW/m^2 for the adequate transmutation capacity and efficiency; but for the present analysis, can be lowered even to that of 0.5 MW/m^2 which is much easier to reach in the near future, and the transmutation efficiency (fission/absorption ratio) is higher than the previous one. The blanket power density is about 200 MW/m^3 which is not difficult to deal with in the practice.

Because of the advantages of low aspect ratio (LAR) Tokamak, it is selected as the driver for transmutation in this paper.

2 Reactor core concept and parameters

A compact Tokamak reactor simply shown in Fig.1 is proposed for the neutron source application, of which parameter requirements, both in plasma physics and nuclear technology, are far less stringent than those in a Tokamak fusion reactor. For several decades, high beta, good confinement and steady-state operation have been pursued by several generations of scientists in magnetic fusion research. To accomplish these goals, LAR Tokamak was proposed about a decade ago. At that time this proposal was not considered in detail, but only for the uncertainties of plasma production. However, HIT[4] and START[5] have successfully proven that LAR plasma can be reliably produced. So LAR Tokamak should obtain enough attention in fusion field. LAR reactor core must be configured for full remote access for the critical components. The critical components include the "diverters", the first wall tiles, the transmutation blanket system, and the normal conducting center leg of the toroidal field coils. The fea-

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tures that can influence LAR reactor core are summarized in Table 1.

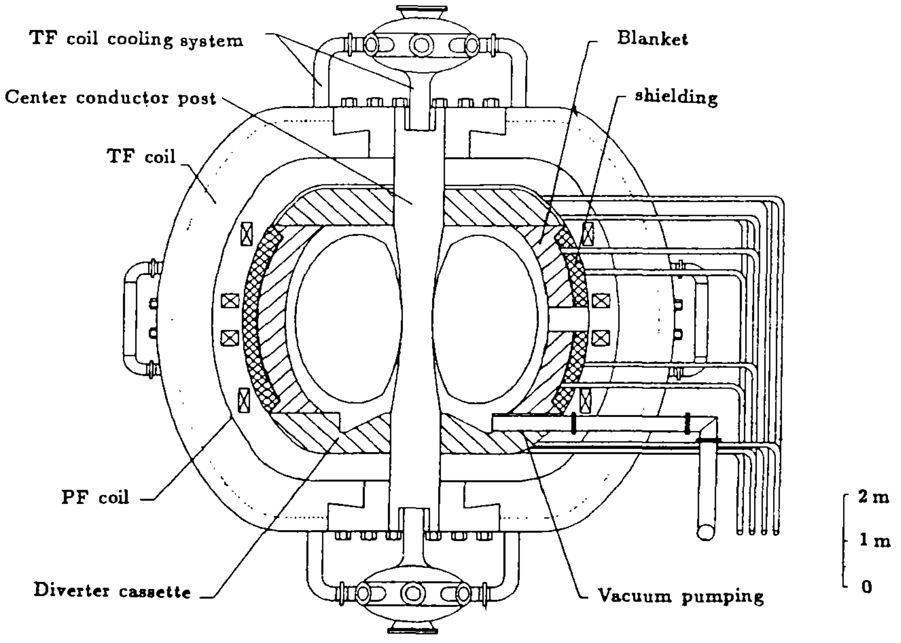

Fig.1 Schematic view of Hefei Low Aspect Ratio Tokamak Reactor (HLAR)

Table 1 Parameter selection of LAR Tokamak reactor core

Major radius, R/m	1.4	1.4
Minor radius, a/m	1	1
Plasma current, I_p/MA	12.54	8.7
Toroidal field, B_t/T	2.5	2.5
Plasma edge, q	4.5	6.5
Average density, $< n_e >/10^{20}m^{-3}$	1.6	1.1
Average temperature, $< T >$/keV	10	9.5
Plasma volume/m^3	50	50
Bootstrap current fraction	0.54	0.4
Fusion power, P_{fu}/MW	100	50
Drive power, P_d/MW	40	50
Neutron wall loading, $P_w/MW \cdot m^{-2}$	1.02	0.5

3 Neutronics of transmutation blanket

A blanket is designed to accomplish dual functions, namely, transmuting the high level nuclear waste (Np, Am, Cm, and Pu isotopes produced in fission reactor) and breeding the tritium for the use in fusion reactor core. Its neutronics analysis is performed by the code, BISON 1.5[6], which was revised by modifying the burnup calculation method and the burnup chains[7] in order to consider the resonance self-shielding effect and more complete burnup process. The original transport data library was

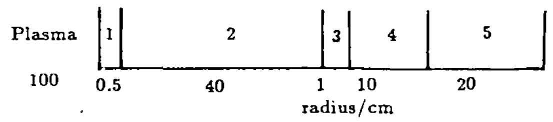

Fig.2 Blanket configuration and material composition

1: ss-316 70%; 2: ss-316 5%+Np-Am-Cm 5%+Pu 1.8% +Zr 1% (neutron wall loading of 1 MW/m^2) or ss-316 5% +Np-Am-Cm 5.7%+Pu 2.1%+Zr 1% (neutron wall loading of 0.5 MW/m^2); 3: ss-316 80%; 4: Li_2O 75% (with ^6Li enrichment 80%) + ss-316 5%; and 5: C 80%

extended to all actinides involved in this issue. But, the analysis presented here neglected to consider the resonance self-shielding effect because it is not serious in the case of fast fission and low K_{eff}. In the revised BISON 1.5, the interface and control are also added to connect THPBHR[8], a code for the blanket thermal-hydraulic analysis with pebble bed.

The one-dimensional lay-out and the material composition of the blanket are shown in Fig.2.

Table 2 gives the results of the nuclides transmuted after 500 d burning. The designs given here are to maintain the Np-Am-Cm transmutation capacity at about 10 times the size of light water reactor (LWRs) normalized to their thermal power. The results show that by raising the fuel loading density, hence raising the $K_{\rm eff}$ and neutron flux, we can reach the transmutation object with lower neutron wall loading ($0.5\,\mathrm{MW/m^2}$), which may be achieved in the near future. For a merit transmutation one of the main figures is the transmutation efficiency, i.e., the ratio of the total fission reaction to the total absorption reaction. Table 3 shows that for neutron wall loading of $0.5\,\mathrm{MW/m^2}$, the efficiency of blanket is so high that the transmutation efficiency and the tritium breeding rate are high enough. The thermal power in the blanket is 4.9 (initial)-3.4 GW (after 500 d) and 9.7~3.4 GW with neutron wall loading $1\,\mathrm{MW/m^2}$ and $0.5\,\mathrm{MW/m^2}$, respectively. Fig.3 shows that in both cases $K_{\rm eff}$ decreases with time, which is beneficial to the safety of the blanket, and T is high so that tritium can be provided for fusion reactors by the present technology used in fast fission reactors.

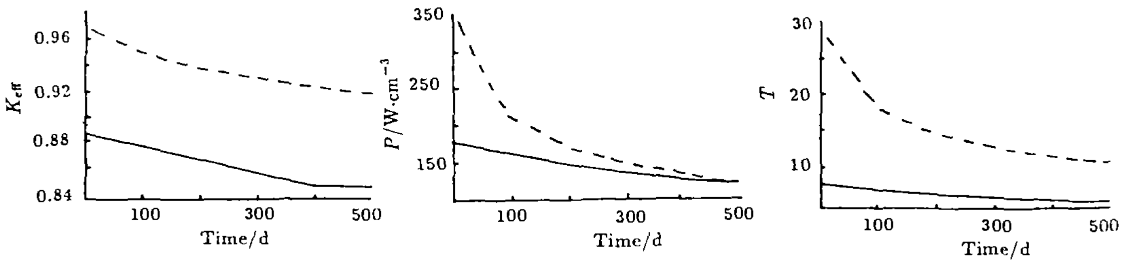

Fig.3 The variations of $K_{\rm eff}$, power density P and tritium breeding rate T with time
— $1\,\mathrm{MW/m^2}$, --- $0.5\,\mathrm{MW/m^2}$

Table 2 The actinides transmuted after 500 d with neutron wall loading of 1 and $0.5\,\mathrm{MW/m^2}$

		^{241}Am	^{243}Am	^{244}Cm	^{237}Np	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu
Nuclides transmuted	$1\,\mathrm{MW/m^2}$	2910	360	-18*	2250	-1107*	1470	270	273	-99*
($\times10^{24}$)	$0.5\,\mathrm{MW/m^2}$	3331	404	-31.3*	2594	-1343*	1532	321	301	-129*
Number of	$1\,\mathrm{MW/m^2}$	13	9	-2*	11	-18*	0.6	0.3	0.8	-0.5*
LWR's**	$0.5\,\mathrm{MW/m^2}$	14	9	-4*	12	-20*	0.6	0.3	0.8	-0.6*
Transmuted	$1\,\mathrm{MW/m^2}$	11	7.8	-2.2*	10	-358*	12.9	5.1	16	-9.3*
fraction(%)	$0.5\,\mathrm{MW/m^2}$	13.3	9.12	-3.9*	11.7	-444*	15.3	6.22	17.5	-12.3*

* negative vaules express the increase of nuclide density

** normalizing method: N =the nuclides transmuted in thermal power hybrid reactor blanket of 1 GW·Year/the nuclides produced in thermal power LWRs of 1 GW·Year

Table 3 Transmutation efficiency (Total fission reaction rate/ (n, γ) reaction rate) for different neutron wall loading

	^{241}Am		^{243}Am		^{244}Cm		^{237}Np		^{238}Pu		^{239}Pu		^{240}Pu		^{241}Pu		^{242}Pu	
Initial	1.0$^{(1)}$	1.1$^{(2)}$	1.4	1.4	3.3	3.4	1.6	1.7	5.3	5.4	14	14	5.0	5.2	12	11	4.6	4.7
After 500 days	1.0	1.1	1.4	1.5	3.4	3.5	1.6	1.7	5.3	5.5	14	15	5.1	5.3	11	12	4.7	4.8

$^{(1)}$For neutron wall loading $0.5\,\mathrm{MW/m^2}$, $^{(2)}$For $1\,\mathrm{MW/m^2}$

4 Natural diverter

The LAR Tokamak configuration offers a possible mechanism to maintain a thick plasma scrape off layer (SOL). An increasing fraction of such a thick SOL becomes diverter naturally without diverter coil in LAR Tokamak. According to the plasma parameters shown above, the distribution properties of the edge plasma parameters near diverter plate of LAR Tokamak are ahown in Table 4. The conceptual structural design of this kind diverter is shown in Fig.4.

Table 4 The main edge plasma parameters for LAR and conventional Tokamak

	LAR Tokamak	Conventional Tokamak
SOL thickness/cm	15	5
Peak ion temperature/eV	14.646	15.6
Peak electron temperature/eV	31.1	157.7
Peak ion energy flux/MW$\cdot$m^{-2}	10.44	8.168
Peak electron energy flux/MW $\cdot$m^{-2}	17.93	50.1
Peak ion density/10^{22} $\cdot$ m^{-3}	1.072	0.37
Peak pressure/Pa	5152	5446
Total energy flux/MW$\cdot$m^{-2}	26.73	55.85
Ion flux/10^{24}m^{-2}	2.796	1.61

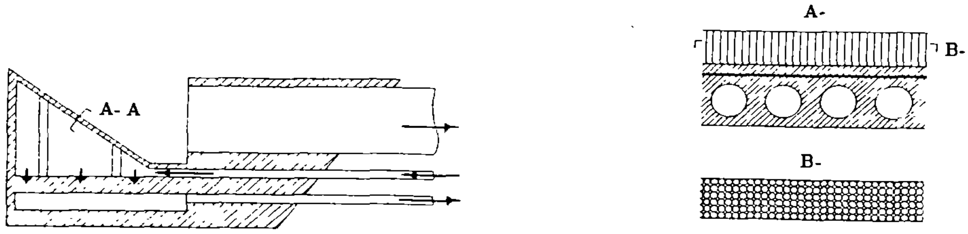

Fig.4 The conceptual structural design of diverter in HLAR

5 Engineering feasibility of center conductor post

A design with an aspect near the lower limit of space requires an unshielded center conductor (CCP) as part of the toroidal field coil. The fully exposed CCP will receive neutron damage, resistive and nuclear heating power, it is one of the key components and requires replacement at regular intervals. The analysis presented here considered a more critical situation (A=1.2) than HLAR in order to examine the engineering feasibility of CCP. Tables 5~10 show the results of the CCP for LAR Tokamak reactor.

Table 5 Parameters of reference design

Reference design	Compact Torus	Regular Tokamak
Major radius R/m	1.2	4
Aspect ratio A	1.2	4
Inner scrape-off layer/m	0	0
Outer scrape-off layer/m	0.15	0.15
Radius of CCP/m	0.2	-
Depth of first wall/m	0.01	0.01
Depth of tritium breeding zone/m	0.5	0.5(inner), 0.2(outer)
Depth of reflector/m	0.2	0.2(outer), 0.5(inner)

Table 6 The average value of neutron wall loading P_w(MW/m^2)

Zone	Total plasma face to component	outer FW	inner FW
Compact Tokamak	1.0	1.023	0.722[(*)]
Conventional Tokamak	1.0	1.083	0.812

[(*)]For the surface of exposed CCP

Table 7 The average value of neutron wall loading H_n (W/cm^3)

Zone	Total CCP	Outer FW	Inner FW
Compact Tokamak	4.35	7.26	6.39*
Conventional Tokamak	—	8.28	5.72

*For the 1-cm-thick surface layer of CCP

Table 8 Design parameters of CCP

Material of CCP	Copper
Current, I_c/MA	4.94
Radius of CCP, R_c/m	0.2
CCP current density, J_c/kA·cm^{-2}	5.31
Surface heat flux, P_w/MW·m^{-2}	4.5
Radius of coolant channel/m	0.005
Coolant fraction	26%
Length of column/m	4.30
Coolant	water
Coolant velocity/m·s^{-1}	6.1

Table 9 Operating parameters of CCP (calculated results)

Coolant pressure drop/bar	5.0
Pump power/kW	14.1
Inlet coolant temperature/K	323
Outlet coolant temperature/K	350.7
Peak copper temperature/K	362.4
Nuclear heating/MW	10.30
Resistive dissipation/MW	22.62

Table 10 Comparison of dpa (displacement per atom) among reference reactors

Ref. reactor	Compact Tokamak			Conventional Tokamak		UWMAK-I	ITER	
Component	CCP	inner FW[(b)]	outer FW	inner FW	outer FW	FW	FW	
Materials	Cu	Cu	Cu	Cu	Cu	316 ss	316 ss	Cu
dpa/year[(a)]	8.7	12.2	14.0	15.5	18.0	18	9.0	11.1

[(a)] normalized to an average neutron wall loading of 1 MW/m^2; [(b)] 1 cm thick surface layer of CCP

6 Future for LAR transmutation reactor

6.1 By comparison with TFTR and JET for the waste transmutation purpose, the requirement of plasma parameters for LAR core is attainable, as shown in Table 11.

6.2 Comparing spallation transmutation reactor with LAR Tokamak transmutation reactor, both concepts have similar target/blanket system, such as subcriticality, low nuclear heat deposit density and optimum high level waste transmutation construction. The only difference is the driver: accelerator or Tokamak. The

Table 11 Comparison of LAR reactors with TFTR and JET

	TFTR	JET	LAR reactor-I	LAR reactor-II
Major radius, R_0/m	2.9	3.0	1.4	1.4
Minor radius a/m	0.9	1.2	1	1
Plasma current, I_p/MA	2	5	12.54	8.7
Toroidal field, B_{to}/T	5	2.8	2.5	2.5
Avg. density, $< n_e >/10^{20}m^{-3}$	0.3	0.4	1.6	1.1
Plasma volume, V/m^3	45	100	50	50
Avg. ion temperature, T_{io}/keV	20	10	10	9.5
Fusion power, P_{fu}/MW	9	15	100	50
Driver power, P_d/MW	30	15	40	50
Bootstrap current fraction	0.4	0.35	0.54	0.4
Duration of D-T burn/s	1	2	s.s.	s.s.
Avg. wall loading/MW·m^{-2}	0.2	0.2	1.02	0.5

selection of drivers depends on the development of the technologies. Table 12 gives the comparison of several approaches for HLW transmutation. One can see that the transmutation prospect of hybrid reactor is very attractive and the technology development anticipation shows that the requirements of HLW transmutation hybrid reactors will be satisfied in the near future.

Table 12 The comparison of different approaches for HLW transmutation

Devices	PWR	FBR	ATW	Hybrid reactor
Neutrons	thermal	fast	intense thermal	thermal/fast
in the device	$10^{14}\cdot cm^{-2}\cdot s^{-1}$	$10^{14} \sim 10^{15} cm^{-2}\cdot s^{-1}$	$10^{16} cm^{-2}\cdot s^{-1}$	$10^{17} cm^{-2}\cdot s^{-1}$
Fission products (Tc, I, Sr, Cs)	yes	no	yes	yes
Actinides (Pu, Np-Am-Cm)	no	yes	yes	yes
Fission material inventory	large	large	small	small
Time for technology advance	0	short	15~20 a	15 a

7 Summary

According to above results, the LAR Tokamak reactor presented here is very attractive and has many advantages such as:

1) Transmutation blanket can be designed to accomplish dual functions, transmuting the high level waste and breeding tritium very efficiently even under the condition of neutron wall loading of 0.5 MW/m^2, which will be reached in the near future. The engineering problems such as heat removing would be solved.

2) Low-A Tokamaks offer the possibility of compact fusion reactor requiring relatively low toroidal field.

3) The natural diverter has wide SOL, which can lower the damage of diverter target plate.

4) The large elongation and high plasma current can be obtained with the simple PF system.

5) The average beta is higher.

6) The longer energy confinement time can be acquired.

7) Low-A has little effect on heating efficiency of α particles

8) Low-A will lead to easily removing of the helium ash

The most serious engineering problem is CCP. But from our analysis, the problem of CCP is not much more serious than that of the conventional Tokamak reactors.

The compact Tokamak might offer attractive advantages if it uses fusion-fission hybrid blanket with large M(10~100). This kind of small reactor could be economically and safely applied by burning long-lived actinide and fission products.

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