A low aspect ratio tokamak transmutation system

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Abstract

A low aspect ratio tokamak energy system has been proposed, which aims at the near time application of the fusion energy. This system include a low aspect ratio tokamak as fusion neutron driver, a Radioactivity Clean Nuclear power System as blanket and a novel concept of liquid metal conductor as center conductor post. On the conceptual design 100MW driver under 1MW/m^2 neutron wall loading can transmute High Level Waste(include minor nuclides and fission products) produced by 10 GW PWR, self-sustain tritium and output a great mount of energy. After the operation of 30 years, the BHP level of whole system will decreased 2 orders of magnitude.

1.Introduction

The principal obstacle to the development of magnetic fusion energy as a commercial electric power is the cost of the first device. The potential impact of various „advanced tokamak" operating modes on power plant prospects has been compared in Ref.[1]. Several different classes of tokamak reactor are considered, and design are optimized in term of cost of electricity (COE) via a coupled physics/engineering/costing code, is 130~70 mill/kwh, higher than coal and APWR: 50~60 mill/kwh beyond the year 2000.

The spherical tokamak (ST) approach appears to provide the indicated way of initiating a fusion development path. The physics key to the attractiveness of the ST approach is in the order unity beta values promised by the combination of high elongation and low aspect ratio. The high beta values β_t~60% mean high power density in small device and low cost and simultaneously ~90% bootstrap current fraction.. The high beta capability means the fusion power density can be so high that neutron wall loading at the blanket, Rather than plasma physics, becomes the critical restriction in Ref.[2] for power plant neutron wall loading has been assumed 8Mw/m^2.

After many year work on fusion-fission hybrid reactor in China option is that fusion energy as commercial energy source is still decades away. The near term usage of fusion power for transmutation of nuclear HLW(High Level Waste) or RCNPS (Radioactivity Clean Nuclear Power System) in which the core plasma parameters and fusion technology requirements as far less stringent, would be advantageous to the eventual development of fusion power as well. Similarly option can found out by Ref.[3]

2.A low aspect ratio tokamak as fusion neutron driver

Table1 gives the features that can influence the low A Transmutation Reactor Core

Tablel 1 Possible core design parameters of Transmutation reactor

Major radius R[m]	1.4	1.4
Minor radius a[m]	1	1
Plasma current Ip[MA]	9.2	7.0
Toroidal field B_t[T]	2.5	2.5
Plasma edge q	5.5	7.5
Average density $\langle n_e \rangle [10^{20}m^{-3}]$	1.6	1.1
Average temperature <T>[kev]	10	9.5
Plasma volume [m^3]	50	50
Bootstrap current fraction	0.72	0.81
Fusion power P_{fu}[MW]	100	50
Drive power P_d[MW]	28	19
Neutron wall loading P_w[MWm^{-2}]	1.02	0.5
Poloidal β_p [%]	0.95	1.09

3. The multi-functional blanket as a novel RCNPS concept[5]

Table 2 gives a blanket configuration. In this kind of blanket, the object is to achieve multi-function: Energy amplifying, HLW transmutation, tritium self-sustaining and fissile material breeding. The operation time is 30 years. Once the certain amount of HLW as spent fuel from PWR are loaded into the blanket initially, the HLW was remained in the blanket and no further HLW added. In order to remain the neutron flux at a certain level, the neutron multiplier(^{233}U) should be added into the blanket after a certain operation time which can be easily fulfilled by adding ^{233}U pebbles and taking out the burned ^{233}U fuel pebbles. At the end of each operation year, the enrichment of ^{233}U is checked so that once the enrichment is over 3%, the Th pebbles are all unloaded and the zone replenished with fresh ^{232}Th(the concentration is the same as the initial loaded one).

Table 2 The 1-D configuration and material composition of multi-functional blanket with Pu as neutron multiplier

Zone No.	*Zone Function ·*	*width (cm)*	*material*
1	Fusion core	100	Vacuum
2	First wall	0.5	ss-316(70%)
3	Minor actinide transmutation	40	ss-316(5%), NpAmCm(4.9%), ^{233}U(1.6%), Zr(1%)
4	Wall	0.5	ss-316(80%)
5	Tritium breeding	5	ss-316(5%), natural Li_2O(5%)
6	wall	0.5	ss-316(80%)
7	Fissile material breeding	10	ss-316(5%), natural ^{232}Th(55%)
8	Wall	0.5	ss-316(80%)
9	Fission product transmutation	20	ss-316(5%), ^{135}Cs(3%), ^{129}I(3%), ^{99}Tc(4%)
10	Reflector	40	C(75%), Be(15%)

The neutron wall loading is assumed as 1 Mw/m^2. Table 3 shows us the calculation results. After 30 Year operation the HLW can be almost burned completely, 2.49×10^{29} ^{233}U nuclides are produced, and meanwhile high M are met and tritium is self-sustained.

Table 3 The HLW in the initial and after 30 year burning and the total ^{233}U produced(10^{24})

	^{241}Am	^{243}Am	^{244}Cm	^{237}Np	^{235}Cs	^{129}I	^{233}U	^{99}Tc
Initial	11080	1959	353	9825	4886	13494		54541
After 30 years operation	3	23.8	25.7	3.67	57.6	18.7	249000	0.007

Fig.1 shows us the power density and the critical factor in the blanket. We can conclude that the critical factor are sustained around 0.95 very well. However, the power density levels of the different blanket zone and in the different operation period are varied very much. The concept shown here is just to show the possibilities of the blanket to reach multi-function. The detailed design should consider more about the fuel cycle for the flattening the power density distribution.

Fig. 2 and Fig 3 show the Biological Hazard Potential(BHP) level of the blanket. The BHP level will raised in the beginning. This is because ^{238}Pu concentration is enriched and the radioactivity ^{238}Pu is much serious that the nuclides evolved to it. But from Fig. 2, even though the BHP is raised much after 10 years burning, initial BHP will decrease very much after decaying for several hundreds of year. After transmutation for 30 years, the BHP can be decreased to less than thirtieth of the initial one.

From the calculation, we can conclude that the blanket have the feasibility to transmute HLW, breeding fissile material both for self-sustaining and other use, breeding tritium for self-sustaining and produce high level power output meanwhile in the relative low fusion neutron wall loading(1 Mw/m^2). The blanket and it's driver can be designed as a Radioactivity Clean Nuclear Power System(RCNPS).

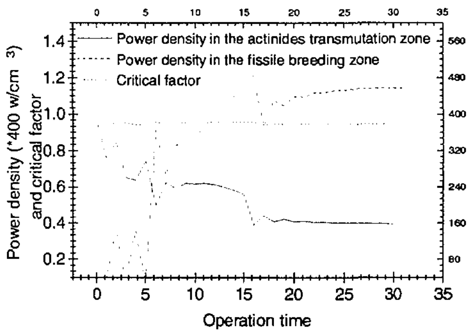

Fig.1 Critical factor, power density vs. operation time.

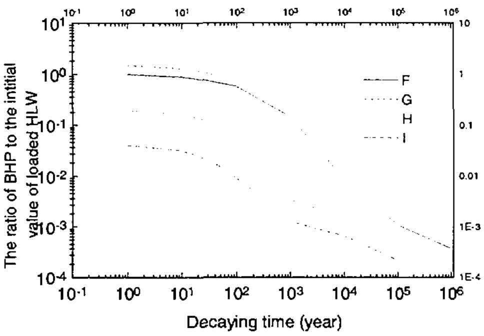

Fig. 2 The BHP vs. decaying time

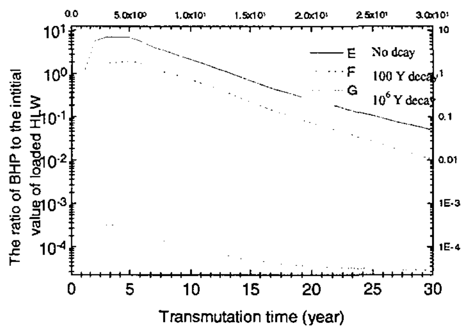

Fig. 3 The BHP vs. operation time.

4. Liquid metal center post[4]

The TF coil center post will have to be periodically replaced at an interval determined by the most restrictive of three considerations:

1. The activation level that is environmentally acceptable for waste disposal
2. Neutron induced structural damage
3. Increase in resistivity from neutron-induced transmutation

Compared with the conventional concept using copper which inevitably meets the above restriction, we suggest that flowing liquid metal Li(or PbLi alloy) inside the replaceable tube(Al, SS) coated by SiC, as the center conductor post.(CCP) Li (or PbLi alloy) has many advantages compared with the copper such as:

1) Less increasement of resistivity under the neutron induced transmutation except the thin layer of the tube. The values of the average DPA-per-full-power-year in the CCP and the FW (first wall) are summarized in Table 4. We found that only 9% of fusion neutrons reach CCP(in the inner FW) and part of those neutrons go through the CCP and the FW into the outer blanket, so displacement per atom (DPA) is much lower, than others.

2) The enhancement of the tritium breeding ratio(TBR). Lithium occupies 80% volume of CCP. The TBR will increase about 5%.

3) Excellent behavior of heat transfer.

The CCP is cooled by coolant flowing vertically through channels (H_2O, He) or tube (Li,$PbLi_{17}$) uniformly distributed in the CCP. In the calculation, four kind of fluids (pressured water, helium gas, liquid lithium and liquid lead-lithium($PbLi_{17}$) have been took as alternative coolants(Table 5).

Table 4 Comparison of DPA for P_w of 1 MW/m^2 for various reference reactors

Ref. Reactor	Spherical Tokamak				Regular Tokamak		UWMAK-I	ITER	
Components	CCP		Inner FW	Outer FW	Inner FW	Outer FW	FW	FW	
Materials	Cu	Li	Cu	Cu	Cu	Cu	316ss	316ss	Cu
DPA/year	3.0	0.7	12.1	15.0	14.0	17.1	18	9.3	10.1

Table 5 Calculation thermal-hydraulic parameters for the CCP

Coolant	Water	Helium	Li	$PbLi_{17}$
Diameter of the post (m)	0.8	0.8	0.8	0.8
Diameter of the cooling channels (cm)	1.5	1.5	1.5	1.5
Plasma current (A)	9.5	9.5	9.5	9.5
Current through the post (MA)	13.8	13.8	13.8	13.8
Resistive heat dissipation (MW)	76.6	77.3	53.5	54.5
Nuclear heat deposition (MW)	7.1	7.1	7.1	7.1
Pressure drop of the coolant (Bar)	0.06	0.009	0.1	0.02
Coolant fraction	26%	26%	80%	80%
Coolant system pressure (Bar)	10	100	10	10
Inlet temperature of the coolant (K)	300	300	460	510
Outlet temperature of the coolant (K)	318	440	564	540
Flowing velocity of the coolant (m/s)	8.6	56	2.1	5.8
Peak temperature in the post	358	516	613	565

5. Summary

1. Low aspect ratio tokamak as fusion neutron driver is very attractive in plasma physics and fusion technology, which can be reached in the near future.

2. One Radioactivity Clean Nuclear Power System (RCNPS) is also reliable, If necessary we can realize no partitioning in the burning process of HLW.

3. Liquid metal center conductor post can save one of key issue of technology for development of the Spherical Tokamak

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