TRANSMUTATION OF HLW (ACTINIDE NUCLIDES AND FISSION PRODUCTS)

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ABSTRACT

The fusion-fission hybrid reactor to be used to produce nuclear fuel which will support PWRs for future energy has been studies in Chinese National Program for a long time. Recently, the study which is to assess the technical feasibility of transmutation of HLW (High Level Waste) by fusion-fission hybrid reactor is going on.

This paper presents two types of conceptual design of fusion-fission hybrid reactor for transmutation of actinide nuclides with nitride fuel or metallic alloy blanket and transmutation of fission product, especially Sr^{90}, with Pu fuel blanket, respectively.

Neutronics and thermal hydraulics calculation was performed to estimate the performance of the whole system. It was found that the plasma core with recently experimental parameters of plasma physics or the ones to be reached in the near future may drive the blanket which transmutes 17% of the loaded fission product Sr^{90} or 23% of the loaded actinides after one year operation at neutron wall loading $1MW/m^2$ and 80% load factor. Thus, the present systems may burn Sr^{90} waste from about 40 PWRs of 3 GW(t), respectively.

INTRODUCTION

The disposal of the radioactive waste generated by the reprocessing of spent reactor fuel is one of the important subject to be overcome in the nuclear engineering. It is particularly necessary to establish the technology for the management of the HLW (high level wastes). A number of actinide nuclides and fission products in the HLW have the hazard potential that remains for millions of years because of their very long half-lives.

One of the widely developing ways for the management of the HLW is the permanent disposal of the waste into a stable geologic formation to isolate them from the human environment. On the other hand, nuclear transmutation is considered as another candidate for the management of the HLW. In this case, the long-lived nuclides partitioned from the wastes are transmuted into short-live or stable one.

Many studies on transmutation of the HLW using fission reactors, particle accelerator and fusion reactors were performed (1,2,3). With a large inventory of the HLW, fission reactors is realizable but have the problem of safety associated with criticality, and it is difficult to get an intensive neutron source and a suitable neutron spectrum for transmutation. Spallation by particle accelerators with much high currents has not yet developed and need certain time (15-20 years) to be realized (3). One of the earliest hopes for the fusion reactor was that they would be used to "burn" fission wastes by neutron transmutation to more benign isotopes, but pure fusion tokamak reactor can't produce enough high neutron flux in the blanket region for transmutation of fission products (e.g. Sr^{90}, Cs^{137}) except high neutron wall loading above $10MW/m^2$(4) which is not acceptable for current level of plasma physics and reactor technology because the capture cross sections of Sr^{90} (0.8b) and especially Cs^{137} (0.11b) are much smaller. How to get high flux of thermal neutrons in the blanket is the key problem for transmutation of fission products. The key issue of transmutation of actinide nuclides is that how to get higher neutron flux at harder spectrum under lower wall loadings.

With recent progress in tokamak plasma physics, the fusion-fission hybrid reactors offer the wide possibilities for the different types of blanket, and offer the attractive advantages if fissile Pu is introduced into the blanket for multiplication of neutrons in the fission product transmutation blanket or new fuel concepts (e.g. Na--cooled or Pb-cooled metal fuel, He-cooled nitride fuel) are used in the actinide transmutation blanket for harder neutron spectrum. The advantages of the fusion-fission hybrid reactor are as follows:

1. The blanket will be safe as a kind of subcritical reactor, and the whole system will work as a passive system;
2. The blanket could produce vast quantities of energy, which could be used as power supply.
3. They will produce higher neutron fluxes under lower neutron wall loadings if fissile Pu is introduced into the blanket for multiplication of neutrons;
4. Harder neutron spectrum will be produced to make transmutation of actinides more effective if metal fuel or nitride fuel is used in the blanket;
5. They will only require lower fusion driver condition than pure fusion reactor, and hybrid reactors may be looked forward to as the first step of reaching the final goal--fusion energy.

CONCEPT OF BLANKET

The flow chart depicting the computer code system for transmutation analysis is presented on Fig. 1. The neutron flux, power density and effective multiplication factor were determined by using 1-D Sn code ANISN(5) and 25-group cross section library UW(6). HLW burnup was calculated by 1-D burnup computation code WTBURA(7) and 46-group burnup data library. Cross sections of HLW nuclides were derived from ENDF/B-IV.

In this paper, two types of blanket were studied.

1. For actinide nuclides.

   The liquid metal-cooled metallic alloy (e.g. Y/Zr) fuel or He-cooled nitride fuel of actinides are used. Metallic fuel or nitride fuel is preferred to oxide fuel because it allows to implement a compact fuel cycle concept based on pyrochemical processes and provides harder

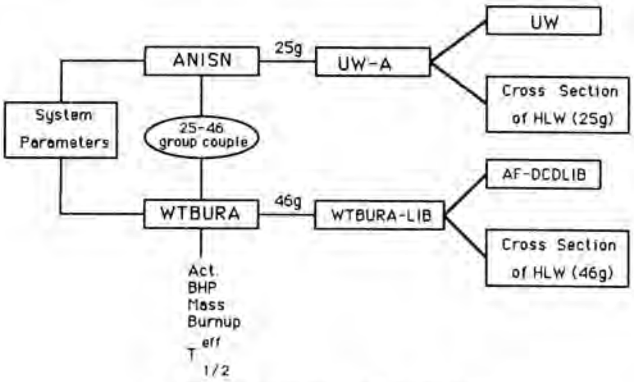

Fig. 1. Computer code system.

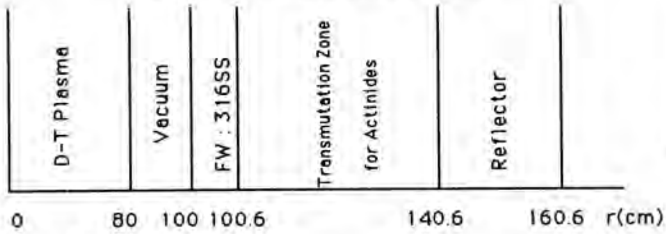

Fig. 2. Blanket for transmutation of actinides.

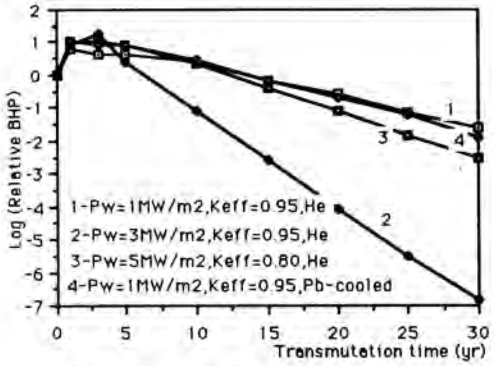

Fig. 3. Relation of relative BHP to time.

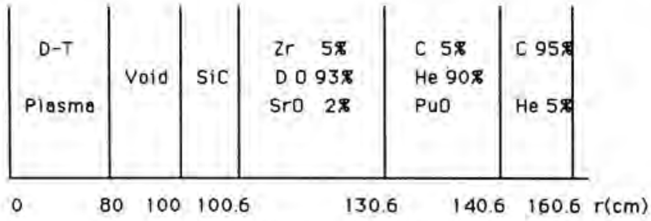

Fig. 4. Blanket for transmutation of Sr^{90}.

neutron spectrum. Harder spectrum make the transmutation more effective. Liquid metal-cooled fuel or particle fuel allows higher power density because of high heat transfer capacity.

As shown on Fig. 2, in the present actinide blanket, the actinide transmutation zone is surrounded by the reflector of stainless steel.

The neutronics computational results of three blankets are summarized in Table I and burnup computational results of He-cooled nitride fuel blanket are summarized in Table II.

TABLE I

The Neutronics Computational Results of Three Blankets.

Blanket	Nitride fuel	Metallic alloy fuel	
		Na-cooled	Pb-cooled
Flux 10^{15}n/cm^2 sec	5.8	6.0	7.9
fraction of >1Mev	22.8%	22.1%	19.8%
Average energy (Kev)	776	759	643
Average power density (MW/m^3)	335	336	379
Initial ratio of fission to capture			
Np237	0.550	0.532	0.555
Am241	0.687	0.666	0.714
Am243	1.297	1.241	1.296
Cm244	2.444	2.369	2.387

The major conceptual design parameters of He-cooled nitride fuel blanket are summarized in Table III and relation of BHP (Biological Hazard Potential) and transmutation time is showed on Fig. 3.

2. For fission product (Sr^{90}).

As shown on Fig. 4, the presented tokamak blanket consists of two zones: the Pu fuel zone (Pu-zone) and Sr^{90} transmutation zone (Sr-zone). In the Pu-zone, particle fuel is loaded, which is suitable for frequent shuffling of fuel and high power density due to extremely large heat transfer area, the Pu fuel is cooled by gaseous He. Sr^{90} is loaded in the chemical form of the oxide SrO. The 14 Mev D-T fusion neutrons

TABLE II

Burnup Computational Results of He-Cooled Nitride Fuel Blanket

Actinide	Charge	Discharge	Burnup		Units of PWR
	(ton)	(ton)	(ton/yr)	(%/yr)	(1GWe)
Np237	9.84	7.37	2.47	25.1	
Am241	8.19	6.49	1.70	20.8	
Am243	1.82	1.38	0.45	24.6	
Cm244	0.42	0.44	-0.02		
Sub-total	20.27	15.66	4.61	22.7	
Pu238		1.82	-1.82		
Pu239	6.72	4.62	2.10	31.3	
Pu240		0.33	-0.33		
Pu241		0.01	-0.01		
Sub-total	6.72	6.77	-0.05		
Other	No	0.66	-0.66		
Total	26.99	23.09	3.82	14.5	65

TABLE III

Conceptual Blanket Design Parameters for Transmutation

Concept of fuel:	
He-cooled, particle fuel	
Depth of transmutation blanket	40 cm
Depth of reflector	20 cm
Effective space factor	0.5
Operation load factor	0.8
Inventory of Np, Am, Cm	20270 kg
K_{eff}	0.95
Average power density	335 MW/m^3
Total thermal power	12 GW(t)
Burnup of Np, Am, Cm	
Kg/year	4610 kg
%/year	22.7%
Units of 1 GW(e) PWR	~65

through the first wall and the fission neutrons from the outer Pu-zone will be moderated in the D_2O-moderated fission product transmutation zone, and a high thermal neutron flux is produced for transmutation of Sr^{90}. The Pu-zone is surrounded by the reflector of graphite. The blanket design parameters are summarized in Table IV.

In analysis, the different influences of the following elements on the effective half-life are considered (See Table V, Table VI and Table VII) (8).

PLASMA CORE DESIGN

During the last few years, continuous experimental and theoretical effort has resulted in progress in tokamak plasma physics (9). The JET tokamak has achieved near breakeven condition. The TFTR tokamak shows the existence of the bootstrap current and the JT-60 tokamak has attained a bootstrap current fraction up to 80%. Efficient current drive with the lower hybrid wave has also been demonstrated in the JT-60 tokamak. The DIII tokamak has demonstrated the Troyon factor g up to 5 (transiently) at high values of edge safety factor q_a, in DIII-D long pulse discharge is achieved with $g = 3.5$.

TABLE IV

Conceptual Blanket Design Parameters for Transmutation of Sr^{90}

Depth of blanket:	
Inner (Sr^{90})	30 cm
Outer (Pu fuel)	10 cm
Reflector	20 cm
Effective space factor	0.5
Operation load factor	0.8
Sr^{90} inventory	3500 Kg
K_{eff}	0.95
Average power density	675 MW/m^3
Blanket power	12 GW(t)
Total flux in Sr^{90} region	$1.2x10^{16}$ n/cm^2S
$T^{eff}_{1/2}$	3.1 year
Burnup of Sr^{90}:	
Kg/year	600
Unit of 1 GW(e) PWR	40

In parallel with these achievements in tokamak research, significant efforts are being made on the conceptual design of the International Thermonuclear Experimental Reactor (ITER) as a next step device towards production of fusion energy. The ITER will be built at the beginning of next century.

The research and conceptual design on fusion core of fusion-fission hybrid reactors producing fuel have been done for many years from 9186 in ASIPP (Institute of Plasma Physics, Academia Sinica). The technology and parameters in the conceptual design (10), many of which are similar to the JET and TFTR, have been reached or can be reached in the near future.

The parameters of the reference conceptual design for transmutation reactor of Sr^{90} and actinide nuclides are summarized in Table VIII.

TABLE V

The Effect of Blanket Compositions

	Blanket Zone Composition (V%)					
Case	First Wall	Transmutation Zone	Reflector	Total Flux in T.Z. ($10^{15}/cm^2S$)	Power Density in T.Z. (MW/m^3)	$T^{eff}_{1/2}$ (Year)
a	C	Zr + D_2O + Pu 5% 95% 0.8166-5[a]	C 95%	23	207	2.23
b	C	C + He[b] + Pu 50% 50% 0.4504-5		30	143	1.80
c	SiC	C + D_2O + Pu 5% 95% 0.4916-5		31	177	1.61
d	Be	Be + He + Pu 50% 50% 0.9113-5		24	226	2.26

[a] 0.8166-5 represents $0.8166x10^{-5}$

[b] 100 atm

TABLE VI
The Effects of Concentrations of Sr^{90}, Pu^{239} and Neutron Wall Loadings

Vol% of Sr^{90}	0	1	2	5	10		
$T^{eff}_{1/2}$(year)[a]	2.23	2.92	3.66	5.33	7.90		
Vol% of Pu^{239}	0.0	0.4982-3	0.1252-2	0.1386-2	0.1449-2		
K_{eff}	0.0	0.5	0.9	0.95	0.97		
$T^{eff}_{1/2}$(year)[b]	16.7	14.0	6.10	3.66	2.32		
P_w(MW/m^2)	0.0[c]	0.5	1	2	3	5	10
T^{eff}1/2(year)	28.8	6.50	3.66	1.96	1.33	0.82	0.41

[a] Assume volume fraction of Pu^{239} is 0.1386×10^{-4} ($K_{eff} = 0.95$).
[b] Assume volume fraction of SrO is 2%.
[c] Natural decay

TABLE VII
$T^{eff}_{1/2}$ of Different Fission Products

Fission Products	Cs^{137}	Cs^{135}	Tc^{99}	I^{129}
$T^{eff}_{1/2}$(year)[a]	11.0	0.72	0.99	0.74

[a] Assume $K_{eff} = 0.95$

TABLE VIII
Parameters of Reactor Core

Major radius	R	3.5 m
Minor radius	a	1.0 m
Elongation	k	1.5
Triangular factor	δ	0.3
Toroidal magnetic field	B_T	6 T
Plasma current	I_p	7.8 MA
Average plasma temperature	$<T>$	14 Kev
Average plasma density	$<N>$	$1.2 \times 10^{20}/m^3$
Energy confinement time	τ_E	1.4 s
Fusion power	P_{fu}	200 MW
Auxiliary heating power	P_{aux}	32 MW
Neutron wall loading	P_w	1 MW/m^2

SUMMARY

- Many difficult and challenging engineering problems can be solved if fusion-fission hybrid reactors are used as HLW transmuters.
- By introducing Pu into blankets as a neutron multiplication materials, a higher thermal flux can be produced under a lower neutron wall loading for transmutation of fission products.
- If liquid metal-cooled metallic alloy fuel or nitride particle fuel is used in the blanket hard neutron spectrum and high neutron flux can be produced, which is hopeful for effective transmutation of actinide nuclides.
- The plasma core in the fusion-fission hybrid reactor, which may drive the blanket for transmutation of the HLW, is realizable.

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