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在中国核能发展中聚变裂变混合堆成本与安全的优势

A COST AND SAFETY SUPERIORITY OF FUSION-FISSION HYBRID REACTOR IN CHINA NUCLEAR ENERGY DEVELOPMENT

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摘　要

从经济和安全角度建立了一种中国核能系统发展规模的优化模型，确定了优化的目标函数，计算和讨论了包含混合堆的中国核能系统的三种发展模式。在与系统外无裂变材料交换的前提下，采用平滑的发展模式，可以展平钚贮存量在核能体系中的分布，减少核能系统的潜在危险，提高投资效益。结果表明，这种优化不仅是必要的，而且还可以在成本和安全方面得到明显的收益。

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ABSTRACT

Considering economy and safety, an optimizational model of nuclear energy developing scenarios of China was set up. An objective function to optimize was determined. Three prospective developing scenarios of China nuclear energy system including hybrid reactor were calculated and discussed. In the system which has no fissile material exchange with other system, a smooth developing model has a smooth distribution of inventory of Pu, thus the potential danger of whole nuclear energy system will be decreased. This scheme will improve investment effectiveness. Result shows that the optimization is necessary and the significant profit in cost and safety can be obtained.

INTRODUCTION

The China energetic development is connected with progress in creation of nuclear fuel cycle (NFC) currently. But it is not difficult to foresee the troubles that will appear in China nuclear energetics (NE) in future. The first is the limited resources of natural uranium. The second is the powerful reprocessing industry to be built. The third is the creation of reliable plutonium storages. The problem of high level waste management will appear in the nearest future. All those problems demand to consider the China nuclear energetic strategy carefully.

The countries developing the NE mainly use thermal neutron reactor with light water coolant (LWR) nowadays[3]. The development of fast breeder reactors (FBR) is the possible solution of the future NE strategy[9]. Now some new alternative plutonium breeders are under the consideration, namely, they are electro-nuclear plant[12] and fusion-fission hybrid reactor (FFHR)[1].

This work is devoted to investigation of possible including in future NE FFHR and considers the possible strategy of China nuclear energetics.

1 NE DEVELOPMENT MODEL

Different models of NE development are existed[1,4]. They are devided into two groups: optimizational models and variant calculation models. The optimizational model is under the consideration in this part.

The optimization in NE means to search the optimum structure of NE under certain system restrictions. The criterion for choosing the best optimum structure is certain objective function. This function is determined by the mathematical model itself. In the model disscussed the objective function is the economic one, that determines the investment in NE diring the calculating time interval.

It is assumed that:

-NE developes step by step, the prognostic period is devided into equal time intervals $\triangle t$, during each interval the NE power is constant and energy production of each type of reactor is fixed;

-the NE additional power $\triangle W_{NE}^{k}$ is input at the begining of current interval with number k ;

-the closed fuel cycle is realized in NE;

-the NE power increase is known.

In order to describe NE development the following system restrictions are used:

(1)Energy production:

$$\sum_{i=1}^{I} W_i \eta_i \Delta N_i^k \geqslant \Delta W_{U5}^k$$

$$\sum_{j=1}^{J} W_j \eta_j \Delta N_j^k \geqslant \Delta W_{Pu}^k$$

Where I, J ——number of reactor types, that use ^{235}U and Pu correspondently, $I \geqslant 1, J \geqslant 1$;

η_i, η_j ——the net efficiency of atomic plant;

$\Delta N_i^k, \Delta N_j^k$ ——additional amount of reactors of I and J type, that can be put into operation at the current interval k ;

$\Delta W_{U5}^k, \Delta W_{Pu}^k$ ——the power increment of I and J reactor type at the begining of interval k ;

$$\Delta W_{NE}^k + \Delta W_{NE}^n = \Delta W_{U5}^k + \Delta W_{Pu}^k$$

and ΔW_{NE}^n ——the total power of stopped reactors, where,

$n = k - T_{work}/\Delta t$ $\quad T_{work}$ ——life time of reactor.

(2)Pu balance in nuclear fuel cycle:

$$\sum_{j=1}^{J} G_j x_j^{ini} \Delta N_j^k + \sum_{j=1}^{J} g_j x_j^{ini} \Delta N_j^k + \sum_{j=1}^{J} \sum_{m=1}^{k-1} g_j x_j^{ini} \Delta N_j^m \geqslant$$

$$\sum_{i=1}^{I} \sum_{m=1}^{k'} g_i x_i^{fin} \Delta N_i^m (1 - E) + \sum_{j=1}^{J} \sum_{m=1}^{k'} g_j x_j^{fin} \Delta N_j^m (1 - E) + C \cdot M$$

Where G_j ——fuel load of reactor;

x^{ini}, x^{fin} ——initial and final Pu enrichment of fuel;

g_i, g_j ——annual reloading of reactor;

M ——total inventory of Pu in fuel cycle;

C ——the coefficient of Pu used in the current interval k ;

$$k' = \frac{k\Delta t - T^t - T^{ch}}{\Delta t}$$

where T^t ——the time of fuel presented in nuclear reactor or reactor blanket;

T^{ch} ——the external fuel cycle time;

E ——part of fuel lost in fuel cycle.

The objective function is as follows:

$$F = \sum_{i=1}^{I} (C_i^c(k\Delta t) + C_i^{ch}(k\Delta t) g_i + C_i^{rr}(k\Delta t) g_i) \Delta N_i^k \cdot \Delta t$$

$$+ \sum_{j=1}^{J} (C_j^c(k\Delta t) + C_j^{ch}(k\Delta t) g_j + C_i^{rr}(k\Delta t) g_j) \Delta N_j^k \cdot \Delta t$$

where

$C^c(k\Delta t)$ ——annual cost of a plant,

$C^{ch}(kM)$ ——the cost of fuel chemical reprocessing;

$C^{w}(kM)$ ——the cost of fuel fabrication and production.

The dependence of cost versus time (kM) is a linear function with 3% per year increase. Thus, restrictions 1 and 2 and objective function F make up so called linear programing task[5]. Unknown variables ΔN_i^k and ΔN_j^k must be determined.

The feature of the model described above is the possibility to change fuel cycle of NE. After the reactor is shut down the device with another fuel cycle can be put into operation to replace stopped one. Because the uranium resourses in China are limited the model is aimed at as fast as possible converting to Pu fuel cycle.

ΔW_{Pu}^k is determined taking into account the total Pu inventory. All Pu available is used during current interval, and $\Delta W_{U5}^k = \Delta W_{NE}^k + \Delta W_{NE}^a - \Delta W_{Pu}^k$. But if $\Delta W_{Pu}^k > \Delta W_{NE}^k + \Delta W_{NE}^n$ then $\Delta W_{U5}^k = 0$, and $\Delta W_{Pu}^k = \Delta W_{NE}^k + \Delta W_{NE}^n$. Pu unused during current interval is accumulated in fuel cycle. Thus, nuclear energetics converts to Pu fuel cycle and the possibility of NE development is created.

2 GENESIS CODE

Computer code GENESIS for IBM PC realizes the model described above. This code has subroutine for solving the linear programming task by simplex-method. Large data bank on energy of nuclear reactors is used in calculations. The code GENESIS itself calculates the nuclear fuel cycle characteristics. Calculation results are presented in tables. Main characteristics of fuel cycle can be ploted. GENESIS can use any set of devices, in present version the set of various devices can consist of 100 kinds of reactors.

3 RESULTS OF CALCULATIONS

Main characteristics of thermal reactors loaded with ^{235}U fuel are presented in Table1. That are the various modifications of WWER reactor (water cooled water moderated energy reactor). Characteristics of thermal reactors loaded with enriched Pu are summarized in Table 2[4]. Here LWR and LWRM are the modifications of light water reactor. Main parameters of fusion-fission hybrid reactors (FFHR1 and FFHR2) are presented in Table 3[2,6,7]. Parameters of fast breeder reactors are presented in Table 4, Here, FROX-fast reactor with oxide fuel, FRH1 and FRH2-fast reactor with homogeneous fuel, FRM-fast reactors with metalic fuel, FRA1, FRA2-fast reactors with alloy fuel. Parameters of nuclear fuel cycle are presented in Table 5[9,10]. The calculations were carried out for 3 variants of China NE development:

(1) Input power is as such[2,8,11]:

$0 \leqslant t \leqslant 30$ a	1.3 GW(e)/a
$30 < t \leqslant 40$ a	0.3 GW(e)/a
$40 < t \leqslant 50$ a	10 GW(e)/a
$50 < t \leqslant 60$ a	26 GW(e)/a

(2) Input power is as such:

$0 < t \leqslant 30$ a	1.3 GW(e)/a
$30 < t \leqslant 40$ a	3 GW(e)/a
$40 < t \leqslant 50$ a	10 GW(e)/a
$50 < t \leqslant 60$ a	23 GW(e)/a

(3) Input power is as such

$0 < t \leqslant 20$ a	1.3 GW(e)/a
$20 < t \leqslant 30$ a	3 GW(e)/a
$30 < t \leqslant 40$ a	5 GW(e)/a
$40 < t \leqslant 50$ a	10 GW(e)/a
$50 < t \leqslant 60$ a	19 GW(e)/a

Table 1 Parameters of thermal reactors with ^{235}U fuel

Type of reactor	W GW(t)	η rel. un	φ rel. un	G t	X^{sm} rel. un	X^{fm} rel. un	T a
WWER1	3.00	0.320	0.80	70.00	0.044	0.010	3.0
WWER2	3.00	0.312	0.80	65.00	0.044	0.013	3.0
WWER3	3.00	0.320	0.80	114.00	0.018	0.008	3.0
WWER4	6.10	0.310	0.80	144.00	0.036	0.009	3.0

Table 2 Parameters of thermal reactors with Pu fuel

Type of reactor	W GW(t)	η rel. un	φ rel. un	G t	X^{sm} rel. un	X^{fm} rel. un	T a
LWR	3.20	0.313	0.75	70.00	0.046	0.012	3.0
LWRM	3.20	0.313	0.75	70.20	0.039	0.014	3.0

Table 3 Parameters of fusion-fission hybrid reactors

Parameter	FFHR 1	FFHR 2
Blanket thermal power, MW	3000	12
Net electricity for sale, MW(e)	1085	3.5
Fissile fuel output, kg/a	1705	100
Total annual cost, M $	112	26

Table 4 Parameters of fast breeder reactors

Parameter		FROX	FRH1	FRH2	FRM	FRA1	FRA1
W', GW(t)		4.2	4.3	4.2	4.2	4.2	4.2
η, rel. un		0.38	0.37	0.38	0.38	0.38	0.38
ψ, rel. un		0.75	0.75	0.80	0.75	0.85	0.75
X^{in}	n. c.	0.12	0.10	0.144	0.107	0.093	0.095
	r. b.	—	—	—	—	—	—
	a. b.	—	—	—	—	—	—
X^{fin}	n. c.	0.110	0.102	0.104	0.101	0.095	0.095
	r. b.	0.020	0.019	0.025	0.018	0.027	0.027
	a. b.	0.009	0.009	0.025	0.007	0.017	0.014
G	n. c.	27.70	36.60	45.50	29.54	42.35	42.35
ton	r. b.	24.00	30.20	37.50	50.36	30.55	30.55
	a. b.	52.80	35.60	37.00	32.52	60.58	19.00
T	n. c.	1.80	1.50	2.09	1.06	2.43	2.43
a	r. b.	1.80	1.50	2.09	1.06	2.43	2.43
	a. b.	2.10	2.00	4.35	1.06	5.00	2.43

Table 5 Nuclear fuel cycle cost estimations

Parameter		WWER	LWR	FBR
Fuel	n. c.	1.5	1.5	1.84
fabrication	r. b.	—	—	1.84
M $ /t	a. b.	—	—	0.48
Chemical	n. c.	0.3	0.3	0.45
reprocessing	r. b.	—	—	0.45
M $ /t	a. b.	—	—	0.20
External fuel cycle time, a		3	3	3

In these variants the China NE power is assumed to be 400 GW(e) in 2050. The possible date of fusion-fision hybrid reactor joined into NE is assumed to be 2015.

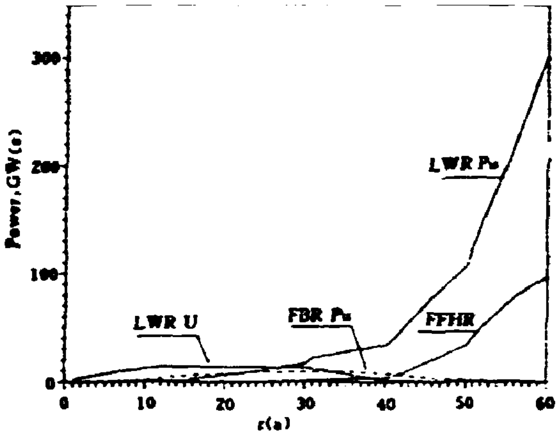

Fig 1　China Nuclear Energetics development

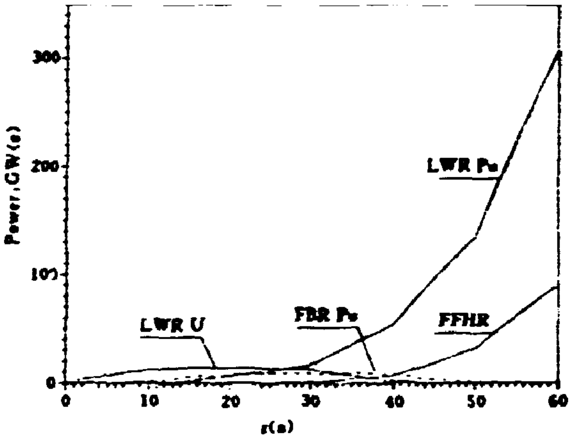

Fig 2　China Nuclear Energetics development

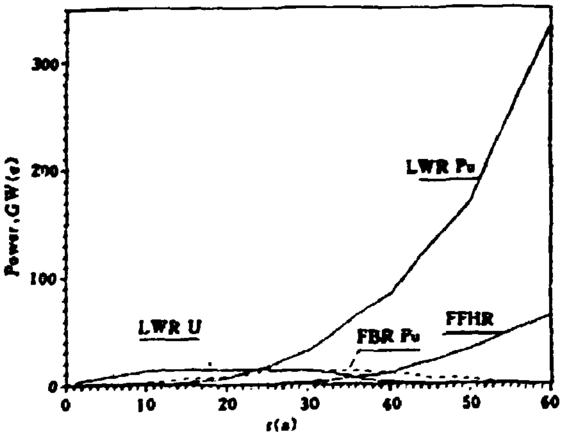

Fig 3　China Nuclear Energetics development

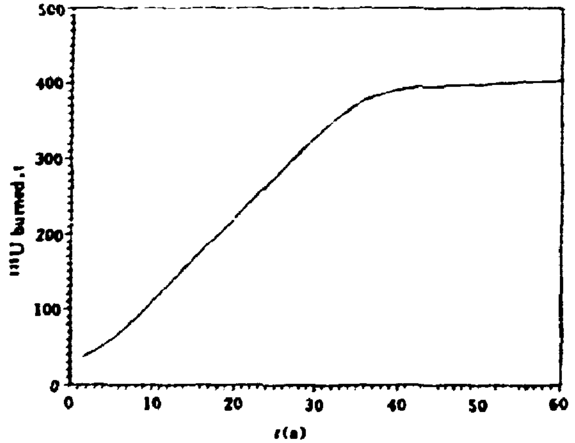

Fig 4　Total amount of ^{235}U burned

The results of calculations for 3 variants are presented in Fig. 1～3. Here: LWR ^{235}U is WWER2 (see Table 1), LWR Pu is LWRM(see Table 2), FFHR is FFHR1 (see Table 3), and FBR Pu is FRA1 (see Table 4).

The total amount of ^{235}U burned for all variants is the same and is shown in Fig. 4. The total Pu inventories in fuel cycle for 1,2,3 variants are presented in Fig. 5. The China NE investments for 1,2,3 variants (including inflation) are in Fig. 6. The relative changing of 1kWh price of electricity compered with 1 variant is calculated and is shown in Fig. 7. The relative incomes from sale of electricity for 1,2,3 variants compered with the first variantare shown in Fig. 8.

The investment in NE for third variant is the hightest. Nevertheless in this case the total energy production of NE increases. Moreover, the lowest accumulation of Pu in fuel cycle is achieved for third variant of development. This in turn decreases the biological danger of whole NE. Such strategy does not demand fast development of the reprocessing industry. In turn this fact can decrease very much the total cost of NE.

4 SUMMARY

The calculations carried out have proved the fact that fusion-fission hybrid reactor is the best breeder for China nuclear energetics. In China NE development, this type reactor is preferable to fast breeder reactor. In this case, the significant profit can be obtained. Moreover, the FFHR put into operation improves the main fuel cycle characteristicts.

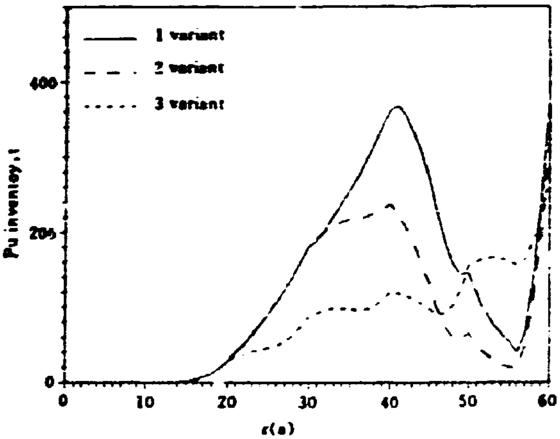

Fig 5 Inventory of Pu in fuel cycle

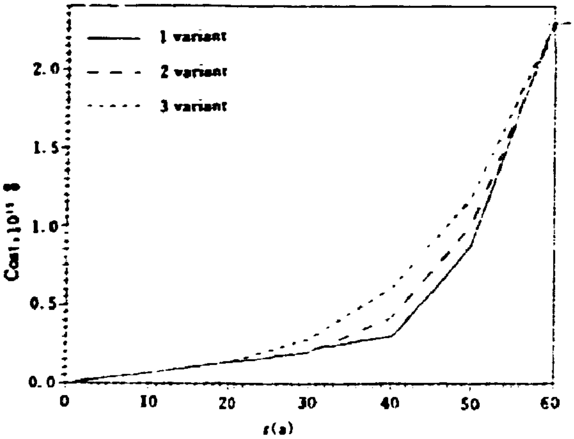

Fig 6 China Nuclear Energetics investment

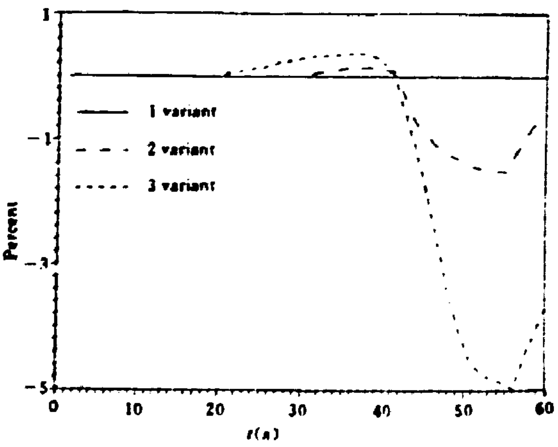

Fig 7 Relative electricity price changing for various NE development strategy

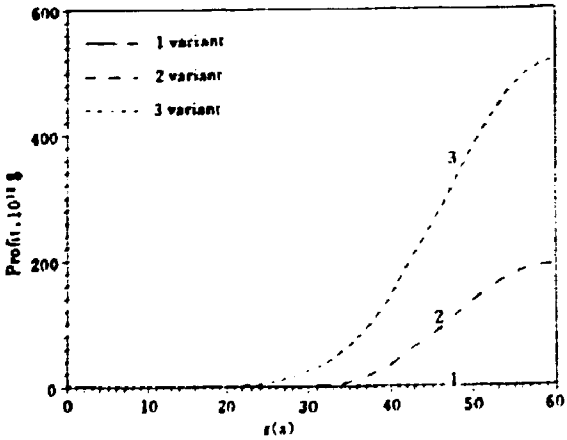

Fig 8 Profit as compered with 1 variant of NE development

The results obtained proved the idea that the total increasing of energy production can give the benefit in electricity cost. The smooth growth of NE power decreases the biological danger of whole NE

Thus, the fusion-fission hybrid reactor due to its attractive characteristics can be the main breeder in China NE.

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