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Preliminary design of hybrid energy reactor and related nuclear fuel cycle

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Abstract

We propose a preliminary design for a fusion-fission hybrid energy reactor (FFHER), based on current fusion science and technology and well-developed fission technology. We list design rules and put forward a primary concept blanket, with uranium alloy as fuel and water as coolant. The FFHER could achieve greater energy multiplication (M>10 for U-Zr alloy fuel and M>5 for UO_2 fuel) and tritium sustainability (TBR>1.05). The sub-critical blanket will last 30 years without re-shuffling fuel. Fission products are the only waste that needs disposal. A new dry process called Fission Product Removal (FPR) replaces conventional reprocessing. It is only necessary to remove the cladding, vent the volatiles and pulverize the solids as feedstock for EM2 fuel fabrication. The AIROX (or DUPIC) process is an example of this operation and has been well demonstrated. After removing the fission products from its 30-year discharge, the refabricated fuel is returned to the reactor for another cycle, thereby reducing the need for enrichment and the proliferation resistance would be increased.

Keywords: Hybrid energy reactor, Alloy fuel, Water coolant, Nuclear fuel cycle ;

1. Introduction

The fusion-fission hybrid (FFH) reactor is not a new idea. Since the initial possibility of harnessing DT fusion, scientists and engineers have realized the potential synergy between fusion and fission. The first concepts, occurring in the late 1950s, were kept classified, due to their promise for breeding plutonium for weapons using

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fusion neutrons [1]. The next several decades (early 1960s to early 1980s) saw a wide range of FFH reactor designs, ranging from fission breeders to fission product transmutators [2, 3]. FFH research in the West was not emphasized in the late 1980s through the early 1990s; however, a revival has occurred since the mid-1990s, as FFH systems are seen as one possible method for dealing with fission spent fuel and for breeding weapon plutonium [4]. Georgia Tech has developed a series of Tokamak hybrids [5-7], which main purpose is the incineration of transuranium isotopes and 3GWth output in the meantime. The LIFE project, which uses an inertial fusion driver, is going on at Livermore National Laboratory. It is fueled only with depleted uranium to reach high burn-up and increase fissile concentrations [8, 9].

In China, FFH systems have been under serious consideration since 1986, as a step towards pure fusion. A variety of FFH design concepts, such as the tandem mirror fusion breeder, the Tokamak engineering test breeder (1986-1990) [10, 11], the Tokamak commercial breeder (1991), have been considered. Going further, a detailed design of a fusion experimental breeder (FEB) (1991-1995), and an engineering outline design study of FEB (1996-2000) have also been performed [12, 13]. These designs evolved from conceptual design to more realistic engineering ones in the research.

ITER is an experimental fusion reactor which has been investigated extensively for years. It cannot achieve the performance required for power reactor operation. Considering the limited availability of uranium, and the growing demand for energy make FFH worth revisiting. The potential advantages of the use of FFH reactors for energy in China are [14]:

1. Energy production with closed fuel cycles and little radioactive waste;
2. Reduction in the mass of spent fission fuel;
3. Production of new fissile fuel; and modest energy production.

A Chinese national project on the conceptual design of a fusion-fission hybrid energy reactors (FFHER) with related verifying experiments, was initiated within the framework of the National Magnetic Confinement Fusion Science Program in May 2010. Based on current fusion science and technology (with some extrapolations from the ITER project) and the well developed fission technology, the project is primarily focused on sub-critical blanket design. The fusion neutron source is based on physics similar to or less demanding than that used for the ITER design, so the existing R&D program supporting ITER will suffice in most physics areas. The reactor technology for the sub-critical reactor should be adapted from the critical reactor technologies (nuclear, fuel, cooling, processing, materials) being investigated in the existing Chinese nuclear program, but these technologies must be modified to provide for the tritium breeding requirement a simplified fuel cycle.

A sub-critical reactor with a fusion neutron source will be more complex and expensive than a critical version of the same reactor. A principal advantage of a sub-critical reactor with a variable strength neutron source is that it can achieve deeper fuel burnup (fuel residence time limited by materials damage rather than criticality) and thus requires significantly fewer complex and expensive fuel reprocessing and refabrication steps.

In this paper the primary blanket neutronics design activities and results are presented in Section 2 and 3. The nuclear fuel cycle are identified also in Section 4. A summary is presented in Section 5.

2. Primary concept design

2.1. Design rules

Concern the safety, proliferation resistance, reliability, maintain-ability, availability, and economics what is more, considering uranium resource and energy demanding in China the hybrid energy reactor rules are:

1. Start from natural uranium, depleted uranium (thorium) or spent fuel. The initial fuel does not require enrichment.
2. Energy multiplication factor is about 10 (M>10 for U-Zr alloy fuel and M>5 for UO_2 fuel) and tritium sustainability (TBR>1.05).

3. The spent fuel could be used by hybrid himself and there is no uranium enrichment nor uranium plutonium separation.. For U-Zr alloy fuel a pyroprocessing could be used and UO_2 fuel the spent fuel could be used directly.

2.2. Modeling tools and procedure

The vertical cross section of the of hybrid energy reactor were shown in fig. 1. As the calculation condition, the two-dimensional cylinder model and the physics parameters were shown in Fig. 2 and Table 1. The height of the model is 10m and we used entirely reflection boundary condition in the top and bottom. The blanket region is divided into four zones, first wall, fuel zone, tritium breeding zone and shield zone. The blanket material and size shows in Table 1. In the fuel zone, the U-Zr alloy fuel is consist of nature uranium (90 wt%), Zr (9.791wt%), Sn (0.159 wt%) and Fe (0.05wt%) and the density is 13.57 g/cm^3, which is 0.85 density of nature alloy for considering accommodate the gaseous fission products. In the case of UO_2 fuel the density of UO_2 is 8.76 g/cm^3.

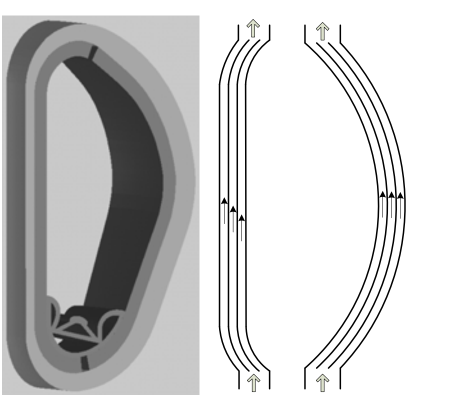

Fig.1. Vertical Cross Section of the of Hybrid Reactor

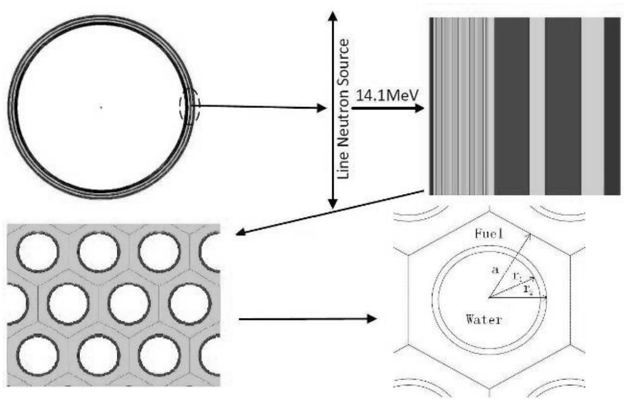

Fig.2. The Structure of Hybrid Energy Reactor

Table 1. Atomic densities of the blanket materials

Zone	Dimension (cm)	Material	Density (g/cm^3)
Cavity	500	Air	0
First Wall	1	SS316	7.98
Fuel Zone	17.15	Fuel (U-Zr)	13.57
	15.11	Fuel (UO2)	8.76
	0.1	Clad	6.44
		Light Water	0.7
Graphite	2 / 0.5	Graphite	2.26
Tritium Breeding Zone	10	Li_4SiO_4	1.340564
	7	Graphite	2.26
	10	Li_4SiO_4	1.340564
	7	Graphite	2.26
Shield Zone	5	SS316	7.98

The light water coolant is in a pressure-tube rather than a pressure-vessel [15], and the density of light water is $0.7 g/cm^3$ in 310℃ and 15.5MP. The radius of the pressure-tube is 0.8cm and 1.2cm for U-Zr alloy fuel and UO_2 fuel respectively. The thickness of the clad is 0.1cm. The tritium breeding material is Li_4SiO_4 and the enrichment of ^6Li is set to 90%. The atomic densities of the blanket materials are shown in Table 2.

Table 2. Atomic densities of the blanket materials

Zone	Material	Nuclide	Nuclei density ($10^{24}/cm^3$)
First Wall Shield Zone	SS316	Si	1.71080E-3*
		Cr	1.66270E-2
		Mn	1.75480E-3
		Fe	5.76500E-2
		Ni	8.18600E-3
		Mo	1.00220E-3
Fuel Zone	Fuel-1 (U-Zr)	^{235}U	2.22469E-4
		^{238}U	3.06760E-2
		^{90}Zr	8.89956E-3
		^{120}Sn	1.08366E-4
		^{56}Fe	7.30484E-5
	Fuel-2 (U-Zr)	^{235}U	1.39600E-4
		^{238}U	1.94080E-2
		^{16}O	3.91040E-2
Tritium Breeding Zone	Li_4SiO_4	^6Li	2.53325E-2
		^7Li	2.41261E-3
		^{28}Si	6.93627E-3
		^{16}O	2.77451E-2
	Graphite	C	1.13415E-1

*1.71080*10^{-3}

Table 3. Parameters of the two models

Parameters	Model-1	Model-1
r1 (cm)	0.8	1.2
r2 (cm)	0.9	1.3
a (cm)	1.37696	2.14751
$V_f : V_w$	2:1	2.36:1
MU (ton)	410.6	271.5

3. Results and discussion

For comparison we calculated two models, the thickness of the fuel zone is 17.15cm and 12.36cm for U-Zr alloy fuel and UO_2 fuel respectively. For burnup calculation we equality divided the fuel zone for five layers.

We developed a calculation system MCORGS, which consists of a Monte Carlo code and a point burnup code. The cross-section library of Monte Carlo is based on JENDL-3.2 [16, 17]. The burnup calculations of one dimension sphere model have been performed by using MCORGS. We set the power of the blanket is constant 3GWth and adjust the fusion power.

Figs. 3-5 show results for effective multiplication factor (K_{eff}), tritium breeding ratio (TBR) and energy multiplication (M), respectively. The energy multiplication factor is the energy released in the blanket per tritium consumed divided by 17.6Mev.

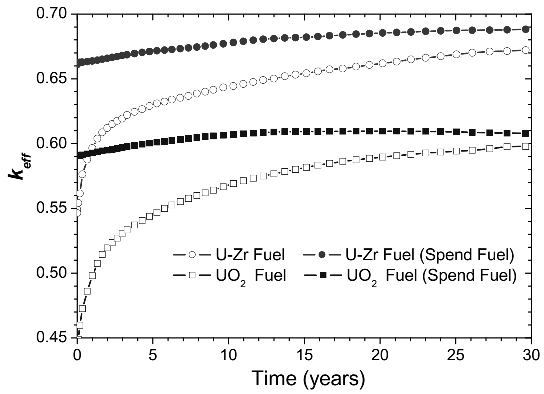

Fig. 3. Burnup calculation results for Keff.

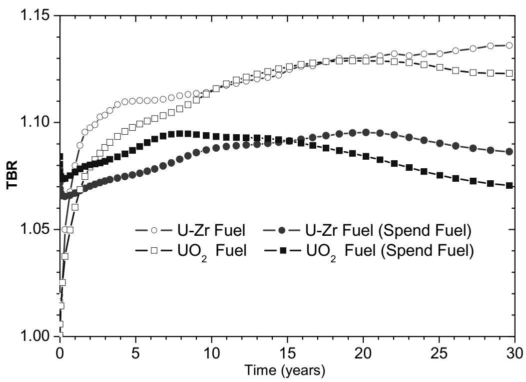

Fig. 4. Burnup calculation results for TBR.

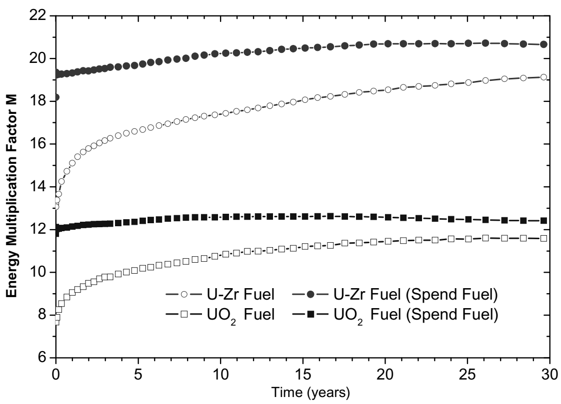

Fig. 5. Burnup calculation results for M.

For the U-Zr alloy fuel model in the equilibrium condition the calculation results shows that the TBR is larger than 1.10 and the energy multiplication factor is about 16. The fusion power is about 200MW and the neutron wall loading is 0.51MW/m^2. For the UO_2 fuel model in the equilibrium condition the calculation results shows that the TBR is larger than 1.10 and the energy multiplication factor is about 10. The fusion power is about 300MW and the neutron wall loading is 0.75MW/m^2, which is close to the ITER condition.

4. Fuel cycle

The FFHER augments its fuel load with nature uranium, spent fuel or depleted uranium. The sub-critical blanket will last 30 years without re-shuffling fuel. Fission products are the only waste that needs disposal. A new dry process called Fission Product Removal (FPR) replaces conventional reprocessing [18]. After removing the fission products from its 30-year discharge, and add 30 tons nature uranium the refabricated fuel is returned to the reactor for another cycle, Figs. 4-5 show the spent fuel results are better than the nature uranium. Thereby reducing the need for enrichment and the proliferation resistance would be increased.

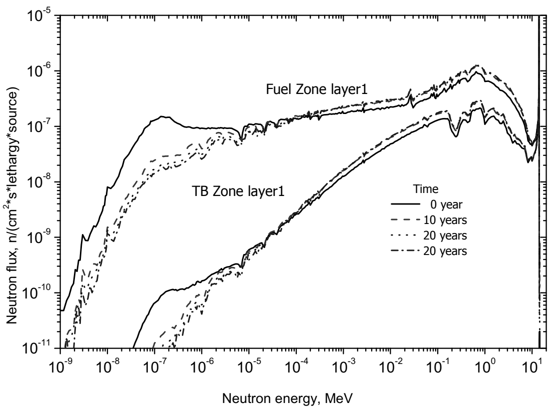

Fig.6 Neutron spectra in the blanket for U-Zr alloy fuel

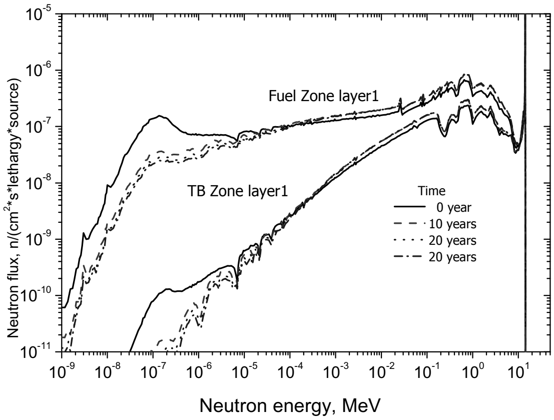

Fig.7 Neutron spectra in the blanket for UO2 fuel

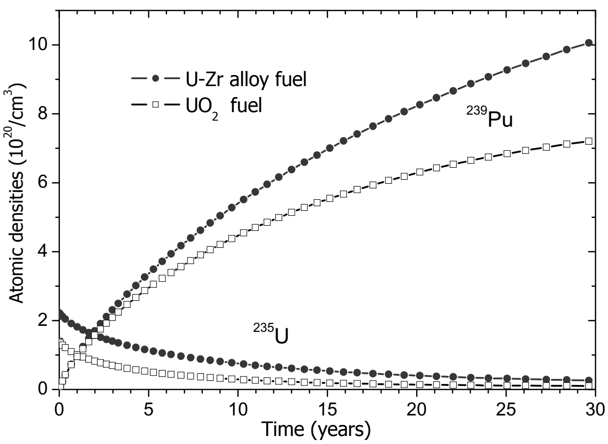

Fig.8 Atomic density of ^{235}U, ^{239}Pu as a function of burnup

Figs. 6-7 show the results of neutron spectra in the blanket for U-Zr alloy fuel and UO_2 fuel respectively. Fig. 8 shows atomic density of ^{235}U, ^{239}Pu as a function of burnup.

In the case of LWR spent fuel, it is not necessary to remove all the fission products or separate the heavy metal. It is only necessary to remove the cladding, vent the volatiles and pulverize the solids as feedstock for EM2 fuel fabrication. The AIROX (or DUPIC) process is an example of this operation and has been well demonstrated.

5. Conclusions

The next two decades are very critical for nuclear energy development. The commercial fast reactor may be in use around 2035. It is also possible that magnetic and inertial confinement fusion will be demonstrated at that time. A fusion demonstration reactor can be a pure fusion or a fusion-fission hybrid. The latter could lower the fusion power and mitigate the radiation damage of high energy neutrons to materials [19].

The fusion-fission hybrid has the potential to make a contribution to waste management, energy production, and fuel supply along a path of long-term sustainability. Other alternatives have been proposed to achieve sustainability, such as fast breeders, fast burners, accelerator-driven hybrids, and repositories of various types. These alternatives are each far more developed than the fusion-fission hybrid.

In 2015 the conceptual design of FFHER and review different concepts will complete, the documents could be "A Technology Roadmap for Fusion-Fission Hybrid Nuclear Energy System". The engineering outline design of FFHER will complete in 2020. In this time, the FFHER could compete against the other alternatives with respect to safety, proliferation resistance, reliability, maintain-ability, availability, and economics in the context of an integrated nuclear energy system.

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