Blanket Concepts for Alternate Fusion Energy Options

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Abstract— **The fusion-fission hybrid concept has attractive applications, including destruction of plutonium and minor actinides, and energy extraction from fissionable materials such as uranium. A fusion-fission hybrid may help to eliminate the plutonium and minor actinides generated as byproducts in the once-through fuel-cycle fission power plants. A fusion power of 1000 MW may help to eliminate 1000 metric tons of fission spent fuel actinides in 100 full-power years.**

Keywords - plutonium; minor actinides; fusion-fission hybrid

I. INTRODUCTION

Fusion neutrons, particularly those produced from deuterium and tritium plasmas, have been considered for alternate applications, other than depositing their energies in a blanket designed entirely for tritium breeding and heat deposition. An attractive alternate application of fusion neutrons is the so-called fusion-fission hybrid. While a pure fusion blanket consists of only non-actinide materials, however, in the fusion-fission hybrid, the blanket contains the uranium and/or transuranium materials (namely the plutonium and minor actinides, which are neptunium, americium, and curium elements). A fusion device is used as a neutron source to sustain the fission reactions occurred in the hybrid blanket. Fission reactions can never be maintained when the neutron source facility, that is the fusion device, is turned off.

The fusion-fission hybrid concept has attractive applications, including destruction of plutonium and minor actinides, and energy extraction from fissionable materials such as uranium. The former application is aimed at destroying the unwanted byproduct transuranium materials generated as byproducts due to the operation of once-through cycle fission reactors while allowing the uranium fuelled light water reactors to continue generating electricity efficiently.[1-10] The latter application allows direct use of natural uranium to generate electricity, similar to the fast breeder fission power plants.[11] Figure 1 describes schematically the fusion-fission hybrid concepts mentioned above. There is also a fusion-fission hybrid concept that aims at producing plutonium as a fuel factory to supply plutonium to the fission power plants when breeding of fuel is inadequate to sustain the fission power. The fusion-fission fuel factory concept had been studied intensively in the 1970s and 1980s in the United States.[1]

Blanket concepts investigated for these fusion-fission hybrid applications include the liquid molten salt and lead or its eutectic (such as Pb-Li or Pb-Bi) used as both coolant and actinide carrying medium, and liquid metal cooled solid Zr matrix that contains dispersed Zr-actinide alloy, such as that developed for the liquid metal fast breeder reactors (LMFBR), had been investigated and reported.[2-11] Molten salt and Zr-Actinide solid blankets are the most investigated blanket concepts and representing the most advanced based on two distinguished neutron spectrum strategies associated with transmutation of actinides. Although there are also possible blanket concepts, but they are either similar in neutron spectrum strategy or not as developed as the molten salt and the Zr matrix based solid blanket concepts.

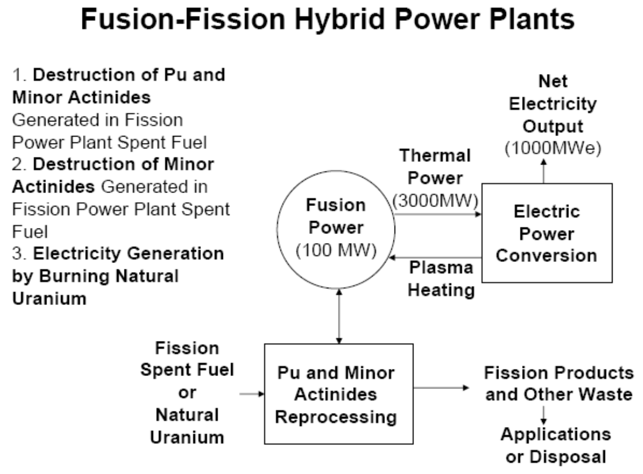

Figure 1. A schematic description of fusion-fission hybrid power plants.

Blanket concepts with the solid zirconium actinide matrix have been studied and were found to be advantageous than the molten salt blankets due to the harder neutron spectrum that renders limited conversion of plutonium into higher actinides.[3,4] Neutronics performance of the molten salt blankets was also found to be less attractive due to the solubility limitation of actinide fluorides in the molten salt.[3]

Recent progress in ITER [12] construction agreement not only helps to pave the way to fusion energy development, but also may influence the development strategy of future fission power plants.[13] One of the scenarios that fusion progress influences is to emphasize the development of advanced once-through cycle fission power plants. If this happens, fusion-fission hybrid may then plays an important role in eliminating the plutonium and minor actinides generated in the fission power spent fuel inventory. This paper is thus focused on discussing to what extent a fusion-fission hybrid

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can help to eliminate spent fuel plutonium and minor actinides. Zirconium matrix based solid blanket was used in the scoping calculations of the potential fusion-fission hybrid because of the promising neutronic performance.

II. SCOPING TOKAMAK CONFIGURATION

Although the tokamak configuration for scoping analysis was chosen for simplicity in understanding the nuclear performance of the fusion-fission hybrid, it is in fact similar to that derived from a realistic tokamak device within the performance limits of present plasma physics and fusion technology database. Such a realistic device has been discussed by W.M. Stacey, et al.[10] Table 1 displays some of the important parameters of this device, and compared with that from the International Thermonuclear Engineering Reactor (ITER) which is being considered for construction.[12]

TABLE I. A CREDIBLE SMALL-SIZE TOKAMAK AND ITS COMPARISON WITH ITER.

Parameter	W.M. Stacey, et al.	ITER
Fusion Power Neutron Wall Loading, MW/m^2	180 MW 0.6 MW/m^2	500 MW 0.6 MW/m^2
Major Radius	3.72 m	6.2 m
Aspect Ratio	3.44	3.1
Plasma Height/Width	1.7	1.8
Plasma Current	8.3 MA	15 MA
Fusion Power/Plasma heating Power	3.1	10
Magnetic Field in Plasma	5.7 Tesla	5.3 Tesla
Bootstrap Current Fraction, %	0.31	
Current drive Efficiency	0.61	

Figure 2 depicts the tokamak configuration used for the scoping calculations. As shown in Fig. 2, it is a medium-size tokamak with a major radius of 3.5 m. The aspect ratio, which is defined as the ratio of the major radius and minor radius, is 7. The minor radius is the radius of the plasma at the mid-plane of the tokamak configuration. The elongation of the plasma, which is the ratio of the vertical radius and the horizontal radius (minor radius) of the plasma, is 2.

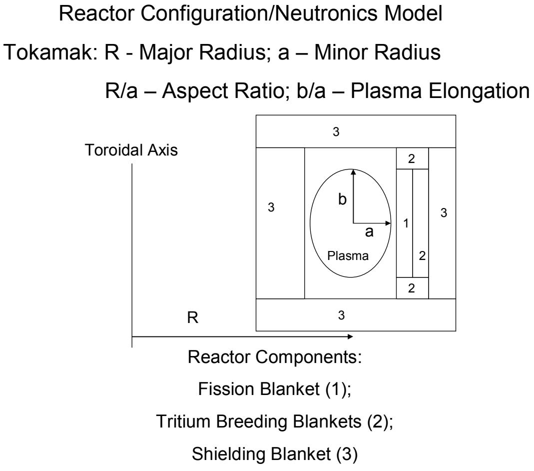

Figure 2. Tokamak configuration for the neutronics calculations.

The fission blanket is located only in the outboard of the tokamak configuration. It is made of ferritic steel, and consists of 10% structure, 80% Zr-actinide matrix, and the balance of coolant. The coolant used in the calculations is sodium, same as that employed in the LMFBR. But there are other possible candidate coolants, such as lead. The density of actinides in the Zr-actinide matrix is 1.15 MT/m^3, corresponding to a 10% by volume of Zr-actinide alloy in the Zr-actinide matrix. The fission blanket is surrounded by helium cooled tritium breeding blankets which consist of 10% ferritic steel structure, 80% tritium breeder, and 10% coolant. The tritium breeder in these blankets is a solid material, $LiAlO_2$, and is enriched with 90% lithium-6 in lithium. For simplicity in designing the tokamak, the inboard region is only installed with the shielding blanket, without tritium breeding capability, as shown in Fig. 2.

Neutronic calculations were performed using the Monte Carlo neutron and photon transport code, MCNP,[14] and the associated nuclear data libraries derived from the evaluated nuclear date files, ENDF/B-VI.[15]

III. NUCLEAR PERFORMANCE AND CHARACTERISTICS

Burn-up of actinides in the fission blanket was taken into account in neutronic calculations in order to reveal the long-term picture of the elimination of the entire spent fuel actinide inventory from the once-through cycle fission power. During the burn-up, however, the fission blanket was assumed to be removed and re-fabricated, when either the structure or the fuel cladding material, which is also made of ferritic steel, reaches the lifetime neutron fluence limit. During the re-fabrication process, the Zr-actinide matrix is reprocessed to extract the fission products for disposal, and the actinides are replenished with the spent fuel grade plutonium and minor actinides. A 0.3 m fission blanket was monitored from the fresh condition with the spent fuel grade actinides to after reaching equilibrium in actinide concentrations.

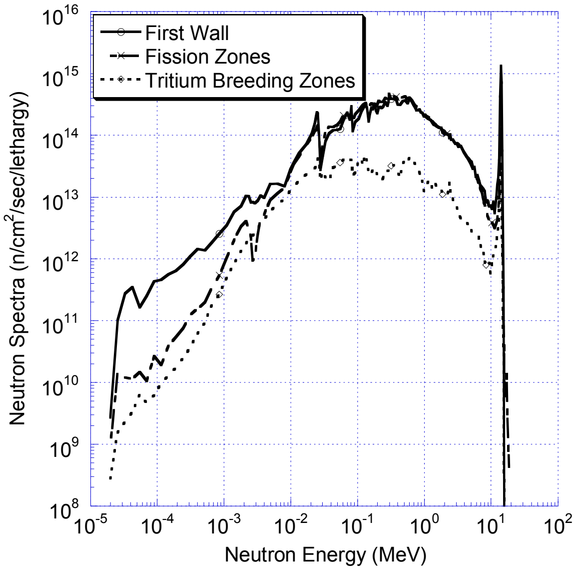

Figure 3. Neutron spectra in the first wall, fission and tritium blanket.

Figure 3 shows the neutron spectrum in the fission blanket. As shown in this figure, the neutron population is dominant in the high energies between 10 keV and 10 MeV, and is peaked between 0.1 and 1 MeV. Figure 4 depicts the criticality factor (k_{eff}), tritium breeding ratio (TBR), and blanket energy multiplication (M), which is the ratio of fission power and the source neutron power (80% of fusion power in the deuterium-tritium fusion fuel cycle), as a function of burn-up in terms of source neutron fluence at the first wall. Figures 4-6 display the evolutional results of burn-up calculations from fresh blanket to equilibrium. Detailed discussions of these results are given below.

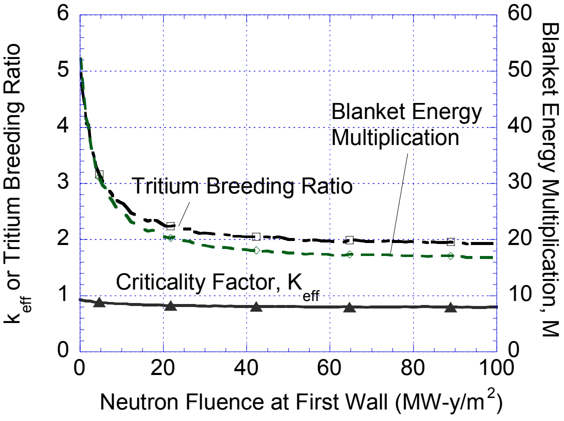

Figure 4. Criticality factor, k_{eff}, tritium breeding ration, and blanket energy multiplication in the fusion-fission hybrid power plant as a function of source neutron fluence.

The initial k_{eff} is about 0.9 and it drops to 0.8 at a source neutron fluence of 20 MW-y/m^2 at the first wall of the tokamak, when the equilibrium condition begins to establish. The equilibrium is then well established after about 40 MW-y/m^2, as shown in Fig. 4. The tritium breeding ratio is more than adequate ever since the initial operation of the hybrid plant. The blanket energy multiplication is initially greater than 50. However, it drops to about 20 after 20 MW-y/m^2, and eventually reaches 17 at equilibrium.

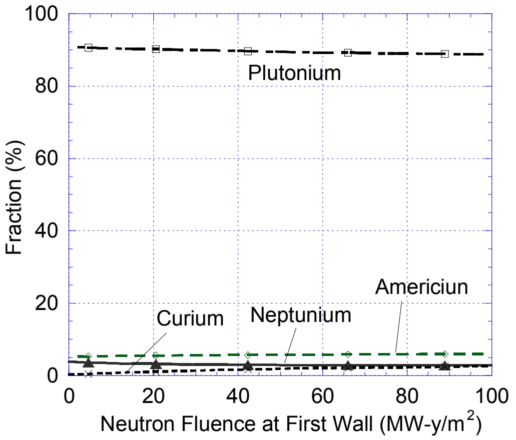

Figure 5. Evolution of Pu, Np, Am, and Cm fractions in the actinides.

Figures 5 and 6 illustrate the characteristics of actinides in the fission blanket. The initial composition of actinides consists of 91% plutonium and 9% minor actinides. The plutonium has 66% in Pu239 and Pu241 fissile isotopes, 2% Pu238, and the balance of Pu240 and Pu242. At equilibrium, the plutonium concentration in actinide composition is about 89%, while the concentration of minor actinides increases to 11%. The ultimate growing of minor actinide concentration is 2% only. The fraction of fissile isotopes in plutonium, however, drops from the initial 66% to 42%, and the Pu238 concentration increases from the initial 2% to more than 4%. This demonstrates that at equilibrium the plutonium in the fission blanket is more proliferation-resistant than that in the spent fuel inventory.

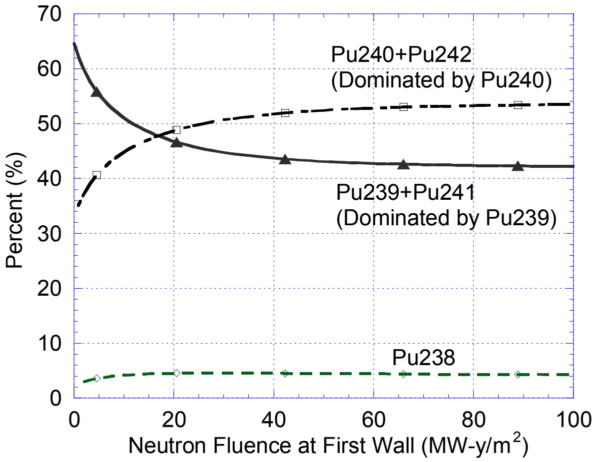

Figure 6. Evolution of plutonium isotopes in plutonium.

The nuclear performance of the fission blanket can be enhanced by increasing the blanket thickness without causing a significant increase in actinide inventory. This can be achieved after the respective actinide concentrations are well adjusted by transmutation into equilibrium. This is a unique feature in the solid blanket, otherwise the initial k_{eff} may be too high, or even exceeding unity to become super-critical, in the thicker blanket case such that it is not realistic to operate as a sub-critical power plant.

TABLE II. CRITICALITY FACTOR (KEFF), TRITIUM BREEDING RATIO (TBR), AND BLANKET ENERGY MULTIPLICATION (M) FOR THE 0.3 M AND 0.35 M FUSION-FISSION BLANKET HYBRID PLANTS.

Thickness of Fusion-Fission Blanket	0.3 m	0.35 m
Actinide Inventory	18 MT	22 MT
keff	0.806	0.895
Tritium Breeding Ratio	1.5	2.5
Blanket Energy Multiplication	17	33
Power Density in Zr-Mixture, W/cc^a	3.1	10

^{a}at a neutron wall loading of 1 MW/m^2.

Calculations were performed for such cases with the equilibrium concentrations of the actinides reached in the 0.3 m fission blanket. Table II displays the results obtained for a 0.35 m fission blanket and compared with that obtained for the 0.3 m fission blanket. As shown in Table II, the k_{eff} for the 0.35 m blanket is increased to 0.895 from 0.806 as in the 0.3 m blanket. The corresponding blanket energy multiplication in the 0.35 m blanket is 33, compared to 17 as in the 0.3 m blanket. Note that the fission reaction rates in the 0.3 m and 0.35 m blanket cases are 1.24, and 2.34 reactions per D-T neutron, respectively. Of which, about 69% occurs in the fissile plutonium isotopes. The remaining 31%, however, happens in the fertile plutonium (mainly Pu240) due to the hard neutron spectrum. This is a major factor leading to the very low transmutation rate of plutonium into americium and curium.

IV. ELIMINATION OF FISSION SPENT FUEL ACTINIDES

Using the two fusion-fission hybrid designs shown in Table II, the plutonium and minor actinides generated in the spent fuel inventory from the once-through fuel-cycle fission power plants can be estimated. A fusion-fission hybrid, dedicated for the destruction of fission spent fuel actinides, 100 MW or 200 MW in fusion power depending on the design of the fission blankets discussed in Section III, can support the operation of 4 once-through cycle fission power plants. Each of these fission and fusion-fission hybrid power plants generates 1 GWe of electric power output.

For the destruction of accumulated fission spent fuel actinides, Fig. 7 displays the estimated full-power years that these fusion-fission hybrid plants take to eliminate 1000 metric tons of spent fuel actinides as a function of available neutron quantity in terms of its corresponding fusion power. As shown in this figure, a fusion power of 1000 MW may take less than 100 years with the higher performance fission blanket (0.35 m blanket), while a fusion power of 2000 MW will be needed if the lower performance fission blanket (0.3 m blanket) is engaged.

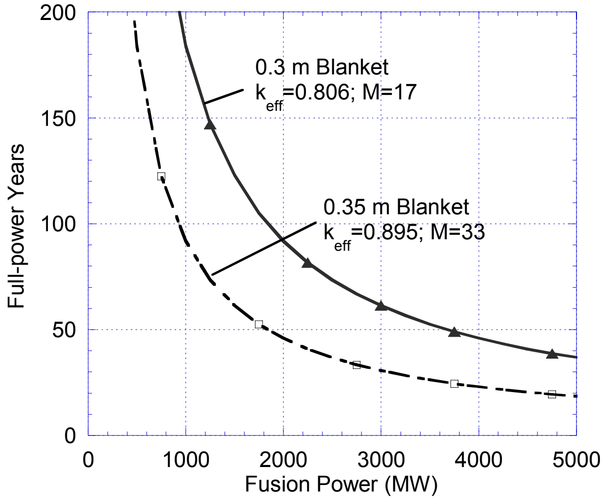

Figure 7. Illustration of scenarios to elimination of 1000 metric tons of Pu and minor actinides extracted from the fission spent fuel: full-power years vs. available fusion power.

A fusion-fission hybrid scenario can be established as follows to eliminate 1000 metric tons of spent fuel transmutation actinides: 10 fusion-fission hybrid power plants constructed, each produces 100 MW or 200 MW of fusion power depending on the fission blanket designs. Each hybrid plant is dedicated to burn one metric ton of plutonium and minor actinides annually. As a result of burning the actinides, electric power output is also expected from these hybrid power plants. The estimated electric power to the grid is 10 GWe from these 10 fusion-fission hybrid power plants.

V. CONCLUSIONS

This study demonstrates that the alternate fusion-fission hybrid power plants can help to eliminate plutonium and minor actinides generated in the once-through fuel-cycle fission power plants. The fusion-fission hybrid concept may also help to pave the way to the realization of a fusion power economy in the long term.

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