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Transuranic transmutation efficiency of a small fusion–fission facility for spent uranium-oxide and inert matrix fuels

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ABSTRACT

The transmutation efficiency of a Fusion facility to Burn Fission Waste (FBFW) based on a Spherical Tokamak (ST) neutron source is investigated. The perfomances are analyzed based on two different fuel cycles. The first fuel cycle assumes separation of all Transuranics elements (TRU) from Spent Nuclear Fuel (SNF) and then burning in FBFW; the second fuel cycle considers a first burning of fissile TRUs in Light Water Reactors (LWR) using an Inert Matrix Fuel (IMF). It is found that the FBFW (1 GWe) can support 5.8 LWR plants (1 GWe) or 19 LWR plants (1 GWe) for IMF fuel cycle. The neutron-dependent characteristics of the system, such as k_{eff} and Tritium Breeding Ratio (TBR), are investigated. The TBR is found to be strongly dependent on k_{eff} and a three-batch strategy is proven to be sufficient to maintain a moderate fusion power (<200 MW) and a satisfactory batch burn-up for IMF fuel cycle.

1. Introduction

The disposal or destruction of fission nuclear wastes has been given growing attention in the last decades. The fission waste inventory is constantly increasing, while the majority of nuclear countries still have to find a final repository solution. Transuranic elements (TRU) are the main contributors to Spent Nuclear Fuel (SNF) radiotoxicity on the long run; if complete removal of TRUs could be achieved, the SNF radiotoxicity would reach the level of natural uranium ore radiotoxicity in about 300 years instead of thousands of years [1]. Different transmutation concepts to burn TRUs have been proposed based on Fast Reactor technology, accelerator driven systems or fusion–fission systems. Early studies on hybrid reactors date back to 1970s [2], however later developments have focused the mission of hybrids on transmutation [3–5], as an efficient way to destroy the Minor Actinides (MA) present in uranium-oxide (UOX) SNF. The effective approach to hybrid transmutation is to use a high multiplication blanket for fission transmutation, and use fusion neutrons only as a subcritical driver [6]. The transmutation potential of a Fusion Reactor based on ITER-like parameters and conventional tokamak technology to burn UOX waste TRUs has been extensively investigated by Stacey et al. [7,8]. Recent studies by Kotschereuter et al. [9] have shown the possibility of burning waste in a small fusion facility and the usefulness of a hybrid system to burn fission waste from LWRs working with Inert Matrix Fuel (IMF). IMFs are part of ongoing studies and research as a way to deeply burn the MAs directly in LWRs [10]. Schneider has shown the burning performances of IMF in LWRs [11] demonstrating the possibility of transmuting most of the fissile TRUs (^{239}Pu, ^{241}Pu) in LWRs. On the other hand, the non-fissile TRUs have relevant fission cross-sections only above the threshold of 1 MeV and do not burn well in a thermal spectrum. However, using a fast neutron spectrum is possible to cause fissions in these non-fissile TRUs and consequently reduce their contribution to radiotoxicity. In this paper, the transmutation capabilities of a Fusion facility to Burn Fission Waste (FBFW) from UOX SNF are compared to the efficiency of FBFW burning fission waste from IMF recycling (viewed as a two-tier fuel cycle). The FBFW is based on the Spherical Tokamak (ST) technology [12,13] that has been proposed as the base for a Component Test Facility (CTF) and for hybrid reactors [14]. The ST technology could be easier to be implemented compared to bigger machines such as ITER. The FBFW is a $Q \sim 1$ ($Q = P_{fusion}/P_{heating}$) machine that can burn fission waste using a moderate fusion power (<200 MW). The performances of FBFW are optimized using a three-batch strategy to maintain continuous operation of the Spherical Tokamak (ST) with a low fusion power. Finally, the dependency of Tritium Breeding Ratio (TBR), a fundamental parameter for fusion system sustainibility, on k_{eff} is also investigated.

2. Fuel cycle scenarios and calculation methods

The geometrical model of the FBFW is shown in Fig. 1 and reactor parameters are given in Table 1. Two different scenarios

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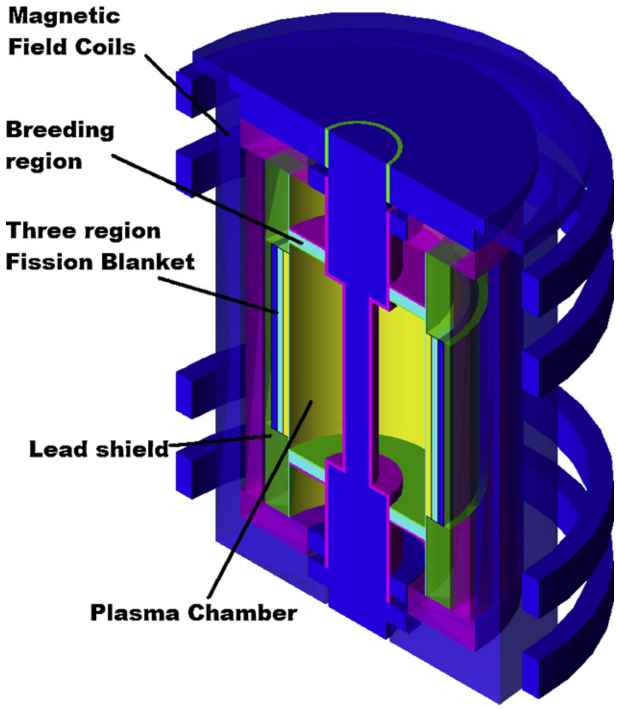

Fig. 1. MCNP5 Model geometry. The Transmutation Fission Blanket is divided into three regions for batch management calculations.

for the use of the hybrid reactor are analyzed. In the first scenario, the FBFW fuel has a TRU composition from typical LWRSNF with a 42 GWd/MTU burn-up after 5 years of cooling, as shown in Table 2. In this scenario, the TRUs are separated from the UOX SNF through aqueous processes or proliferation-resistant pyrometallurgic reprocessing and new fuel pins are fabricated with TRUs in a Zr matrix. The fuel pins composition used is: TRU 19 w/o, Zr 81 w/o.

Table 1
Spherical Tokamak design parameters.

Major radius, R	1.2 m
Minor radius, a	0.8 m
Elongation, κ	3.2
Fusion power	100–200 MW
Neutron wall load	1.0–2.0 MW
TRU blanket height	4.8 m
TRU blanket thickness	53 cm

Table 2
Nuclear waste compositions. Composition of TRUs in UOX SNF (enrichment 4.5%, 42 GWd/MTU) by mass percent, after 5 years of cooling. Data calculated with Origen-Arp. Compositions of TRUs in IMF waste are normalized (to a sum 100%) from the results discussed in Ref. [6]. The masses loaded in FBFW are 15.5 tons for UOX SNF and 32.36 tons for IMF.

	SNF	IMF
Np-237	5.2647	3.3353
Pu-238	1.9679	13.4472
Pu-239	52.3530	3.5647
Pu-240	20.6830	10.6942
Pu-241	10.1854	6.0707
Pu-242	4.8269	35.7887
Am-241	3.2624	0.3282
Am-242m	0.0106	0.0071
Am-243	1.1341	10.0589
Cm-242	0.0001	1.8000
Cm-243	0.0036	0.0847
Cm-244	0.2916	13.6943
Cm-245	0.0154	0.5541
Cm-246	0.0013	0.5718

The FBFW blanket, where the fuel pins are loaded, is helium-cooled with 62% He and 8% ferritic steel structure by volume. The fission blanket is surrounded by lead for neutron reflection and shielding. The main limit to the maximum TRU load is given by the requirement of having a subcritical system. The FBFW is designed to be subcritical even in case of total loss of coolant, in fact k_{eff} is expected to increase with no coolant due to the fact that TRUs fission better in a harder spectrum. With this design goal, the total mass of TRUs that can be loaded is 15.5 tons, most of which is made of Pu isotopes. A nuclear power plant of 1 GWe produces about 20 metric tons of UOX SNF per year of which 1% is TRUs; therefore 15.5 tons are the total TRUs produced by 77 LWRs in a year. A different composition of TRUs coming from IMF waste is used in the second scenario. In this scenario, the TRUs from UOX SNF are first reprocessed as IMF fuel to be burned in LWRs, so to reduce the Pu and other MA content and achieve a 70% TRU burn-up. The IMF waste is therefore poor in fissile nuclides such as ^{239}Pu, since these nuclides are burned in LWRs; the IMF waste TRU composition is taken from Ref. [6] with a 650 MWd/kg IHM burn-up and shown in Table 2 for comparison with SNF composition. The IMF waste TRUs are then reprocessed as FBFW fuel in a Zr matrix with a TRU content of 37 w/o. The total mass of TRUs in FBFW blanket is 32.36 tons in this second scenario; in this case, it is possible to store a higher mass of TRUs in FBFW blanket, since fissile nuclides are small constituents of IMF waste. Considering that LWRs are able to burn 70% of UOX SNF TRUs in IMF [6], the load of TRUs in FBFW corresponds to the TRU waste coming from initial 539 LWRs.

The tritium breeding zones of FBFW are located in the divertor regions. No breeding is pursued in the fission blanket to avoid competing of ^{6}Li absorption reactions (n,p), (n,t), (n,nd) with TRU fissions. The cross-sections of these reactions can be as high as 25% of the value of the TRU fission cross-section (about 2 b) at energies above 1 MeV. The solid breeder considered in the present analysis is Li_3TiO_3 with a 90% enrichment in ^{6}Li.

The fission blanket is divided into three regions to analyze the efficiency of a batch fuel management strategy. An in-to-out batch strategy is chosen: at the beginning of each cycle a new batch of fuel is inserted in the region closer to the plasma wall. In this way, a part of the fuel is always fresh and the multiplication factor of the FBFW is maintained high.

The neutronics calculations have been performed using MCNP 5 1.5 [15], while for burn-up calculations the ORIGEN 2.2 [16] was used. The two codes are coupled through a modified version of the coupling utility MONTEBURNS 2.0 [17]. MONTEBURNS has been modified to output the neutron source used in calculations and the intermediate MCNP tallies. Data from ENDF/B-VII.0 were used for neutron cross-sections.

3. Results

3.1. Transmutation efficiency and burn-up calculations

The transmutation efficiency, defined as percentage of the actinides destroyed at the end of the cycle from the initial load, is first analyzed for one-batch-mode. The fresh fuel is loaded in the FBFW and is let to burn for 5000 days (∼13.7 years). The calculations are performed with a constant blanket output power of 3000 MWth, attributed to the 14.1 MeV neutrons that constitute 80% of the fusion power. Assuming a 33% efficiency, the FBFW has an electrical output of 1 GWe. The fusion power of ST is automatically adjusted based on the thermal power produced in the fission blanket. Maintaining a fixed thermal power output allows a constant energy production from the FBFW. The goal, though it needs support from further economical analysis, is to produce a substantial amount of electricity from FBFW, so that the device can at least

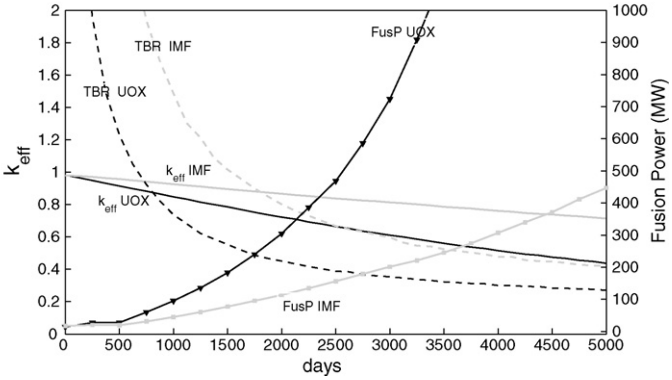

Fig. 2. k_{eff} and fusion power behavior for TRU burning from UOX SNF and IMF waste. The TBR for the two systems is also shown.

recover all the capital costs, without bringing additional costs on the fission nuclear fuel cycle.

Fig. 2 shows that the fusion power increases exponentially as k_{eff} decreases, where k_{eff} indicates the subcritical multiplication constant for a source driven system. The TBR is shown to be strongly dependent on the neutron population in FBFW. Despite the fact that the breeding regions are in the divertor area, the fusion neutrons contribute only to 0.25 of the total TBR, while the rest of the TBR is provided by neutrons produced by fissions in the blanket. Since the FBFW will operate on a range of k_{eff} values, a range such as to provide an effective TBR will have to be chosen to design a fusion transmutation compact system. Exploiting most of the neutrons leaking out of the fission blanket the FBFW will be able to achieve a breeding in a much smaller area than a pure fusion reactor. Fig. 2 shows that TBR decreases to a value of 0.26 for UOX SNF when k_{eff} is 0.4 and the effect of fission neutrons on TBR becomes small. For the IMF waste TBR is maintained above 1 for a time period greater than 700 days, however with the burn-up and k_{eff} decrease the TBR drops exponentially to a value of 0.4. Such a great change of TBR in time should be avoided during normal operations. The FBFW should be carefully designed to maintain TBR as constant as possible over time. This goal could be achieved by geometrically increasing the coverage fraction of the breeding zones that are directly subjected to fusion neutrons or by operating the facility at a constant k_{eff} as long as possible. Fig. 3 shows the TRU inventories during a 5000 day time frame for the UOX SNF waste transmutation. It is observed that all TRUs except Cm isotopes decrease during the fission burn-up. Fig. 4 shows that TRU inventories for IMF waste transmutation. The net TRU transmutation rate (destruction less production of new actinides) is constant for most of the burn time.

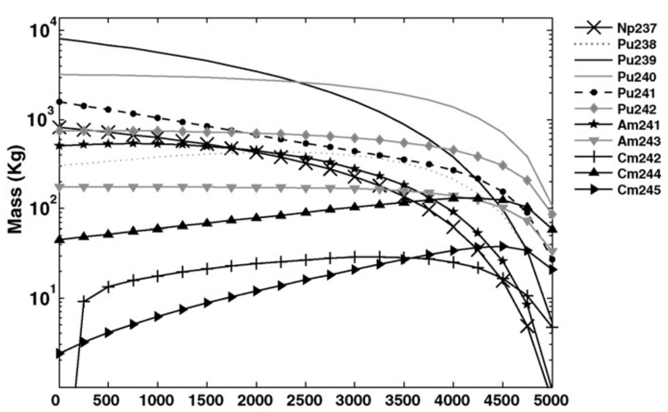

Fig. 3. TRU inventories vs. time for UOX SNF waste burning.

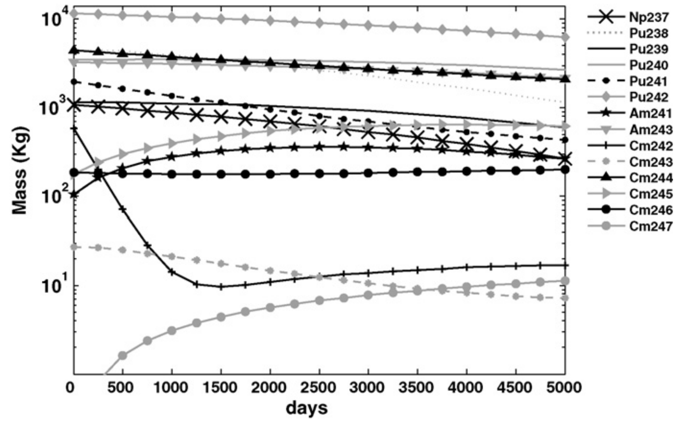

Fig. 4. TRU inventories vs. time for IMF waste burning.

It is found that the first scenario can burn a TRU amount of 1.16 tons per year corresponding to the waste of 5.8 1 GWe LWR power plants, a perfomance that slightly outperforms classical tokamak transmutation [8] and ICF driven transmutation [5]. For the second scenario, a destruction of 1.16 tons is still achieved; this corresponds to the waste originally produced by 19 1 GWe LWRs which has gone through a burning stage with LWRs using IMF. After 5000 days (~13 years) a 48% burn-up of IMF waste is reached, while 50% burn-up is reached after only 2500 days for SNF waste of scenario I, since ^{239}Pu, which is the main nuclide in the UOX SNF case, burns more rapidly in the transmutation reactor and the TRU mass loaded is about half of the TRU mass loaded in the IMF scenario.

3.2. Batching strategy to maintain constant fusion power

Analyzing the first scenario, it is found that the fusion power ends being much higher than the design goal of 200 MW. To maintain the ST fusion power within the design goals, a three-batch strategy was adopted in Scenario I where a portion of fresh fuel is replenished in the reactor at constant intervals. Fig. 5 shows the k_{eff} and the required fusion power for a three-batch strategy where material shuffling takes place every 1000 days. The reactor is started with all fresh fuel and every 1000 days a batch of fresh fuel is added in the inner region close to the plasma while the outer batch is discarded. The k_{eff} decreases constantly during each time step and every 1000 days increases due to the discrete feeding of fresh fuel. This batch strategy permits to work with a k_{eff} varying from 0.7 to 0.8 after the fourth batch cycle. The total residence time for every batch is 3000 days; at the end of the residence time a batch has reached a burn-up of TRU elements of 60%. After 3000 days the

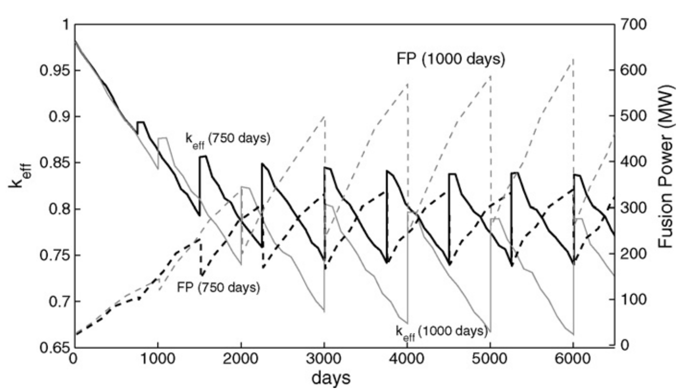

Fig. 5. k_{eff} and fusion power behavior for two different batch management strategies for UOX SNF: 1000 days batch shuffling and 750 days batch shuffling.

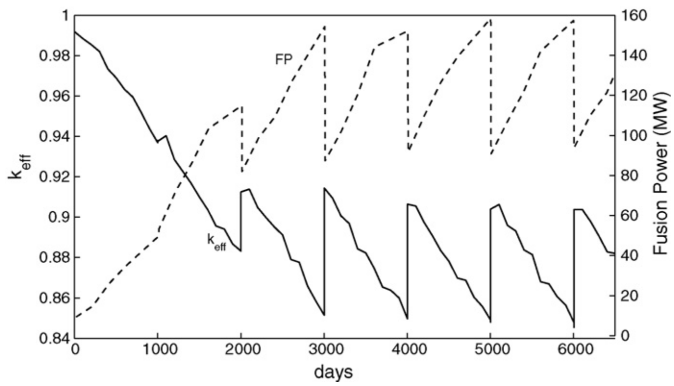

Fig. 6. k_{eff} and fusion power for a batch management with residence time of 3000 days per batch for IMF waste transmutation.

batch is discharged from FBFW and is sent to further reprocessing. However, this strategy still requires a considerable amount of fusion power 300–600 MW, which is outside the range of the design goals. A second batch management strategy is shown in Fig. 5 with a batch cycle of 750 days. In this case, the FBFW k_{eff} varies between 0.75 and 0.85; reducing the demand of fusion power to a range from 180 to 350 MW. In this case, a 45% TRU burn-up is achieved for every batch with a residence time of 2250 days. Lastly, a batch strategy for IMF waste transmutation is shown in Fig. 6. In this case a residence time per batch of 3000 days was chosen; calculations show that this corresponds to a burn-up of 30%, a good burn-up rate for the non-fissile IMF waste. In this case the fusion power at the beginning of step is reduced to 90–160 MW, within the design goals.

These results show that an IMF fuel cycle could relax the fusion driver requirements compared to a UOX SNF transmutation for the same type of machine. Moreover, the IMF fuel cycle with a three-batch strategy would be able to roughly support 19 LWRs, even though a previous pass in LWRs is required for IMF. If TRU destruction in LWRs using IMF is proven to be viable, then a machine like FBFW could be a great transmutation solution for inert matrix spent fuels. However, further studies are needed to design the FBFW on the burned fuel composition reached after the fourth batch cycle so to operate with a high k_{eff} from the beginning of operations, avoiding the initial k_{eff} decrease and exploiting the full capabilities of the hybrid with the use of a special-designed fuel for the start-up phase.

4. Conclusions

An analysis of the transmutation capabilities of a compact fusion facility was performed. It was calculated that such a facility can effectively burn the UOX TRU fission waste of 5.8 1 GWe LWRs. The FBFW is also able to burn IMF fission waste coming initially from 19 LWRs after a previous reduction of fissile TRUs in LWR. For this case, a batch fuel management strategy shows that the FBFW can operate with a low fusion power (<200 MW). The TBR was shown to be strongly dependent on the fission neutron population, despite the fact that breeding was not achieved in the fission blanket, but in regions more directly exposed to fusion neutrons. However, a small size fusion facility shows great potentiality for transmutation of both UOX SNF and IMF waste. Further studies are needed to design the system to operate with a stable high k_{eff} from the beginning of operations and with a constant TBR.

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