A FUEL CYCLE FOR MINOR ACTINIDES BURNING IN A STELLARATOR-MIRROR FUSION-FISSION HYBRID

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The MCNPX Monte-Carlo code has been used to model a concept of a fusion-fission stellarator-mirror hybrid aimed for transmutation transuranic content from the spent nuclear fuel. A fuel cycle for the subcritical fusion-fission hybrid is investigated and discussed.

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INTRODUCTION

Nuclear energy will occupy one of the main positions in the energy supply of mankind in the coming decades and in the near future. It is directly related to the amount of proven uranium reserves in the nature [1]. Besides, economically the electricity generated by nuclear reactors is one of the cheapest [2]. However, with using of nuclear energy a number of problems arises one of which is handling of spent nuclear fuel.

Utilization of spent nuclear fuel is an actual global problem. The long-term radiotoxicity of the nuclear waste (Fig. 1) is clearly dominated by actinides [3].

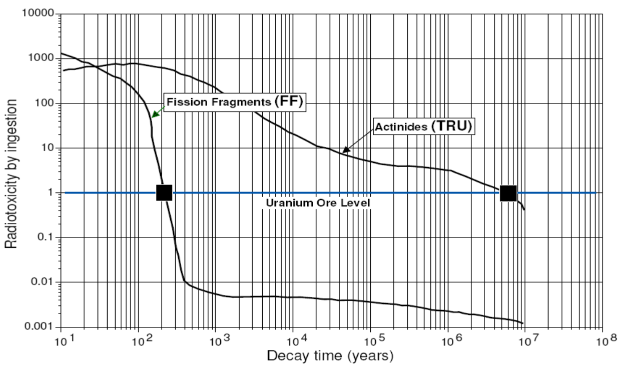

Fig. 1. Time evolution of the potential radiotoxicity (relative to uranium ore) of the two main components of nuclear waste for PWR spent fuel

All actinides are fissionable elements and may be incinerated by fission which is also accompanied by substantial energy release. Fission produces fission products which are less radioactive in long term, and after 200…300 years they could be removed from the repository. Burning transuranic (TRU) elements could be made in nuclear reactors, especially in fast because not all the TRU are fissile by thermal neutrons.

The idea is separation of TRU and then burning them separately. Nevertheless, this technology has some problems:

- Fast reactors are critical.
- Fuel with transuranic elements has a deficit in delayed neutrons, which decrease the reactor controllability [4, 5].
- Unlike pressurized water reactors (PWR), reduced value of the Doppler-effect at the fast reactors leading to deterioration of nuclear safety in the case of accident situations, such as increase the temperature of the fuel in the reactor core.

Based on the above, we can conclude that the transuranic elements can be only small portion of the fuel, and this hinders their transmutation in significant amount.

Thus, an attractive idea is development of a subcritical reactor, the main purpose of which will be a safe burning of transuranic elements of the spent nuclear fuel. The subcritical reactors, which are controlled by external neutron sources, are more complex and costly, but have certain advantages as compared with critical reactors. Together with efficient power production the subcritical reactor has an improved controllability of the chain fission reactor that boosts reactor safety.

Since for fast neutrons fission cross-section is much smaller than for thermal neutrons, to provide an appropriate reactivity of the reactor, the fuel should contain significant portion of fissionable material. Therefore, until the radioactive damage destroys the fuel, the percentage of burned minor actinides cannot be high. The fuel cycle of transuranic fuel, which is loaded into the subcritical reactor core, is then of particular interest.

CONCEPT OF STELLARATOR-MIRROR HYBRID

In Ref. 6 a stellarator-mirror hybrid reactor (Fig. 2) is proposed.

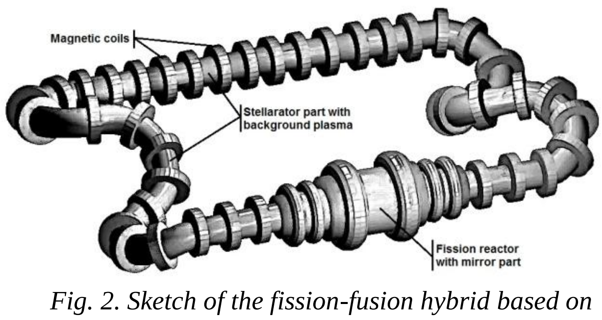

Fig. 2. Sketch of the fission-fusion hybrid based on DRACON [9]

It consists of a magnetic trap for plasma confinement in which fusion neutrons are generated and a sub-critical fast reactor driven by these neutrons. The magnetic trap is of a combined type: it is a toroidal stellarator with an embedded magnetic mirror with lower magnetic field.

The stellarator part provides confinement of warm dense deuterium target plasma. Hot sloshing tritium ions are confined at the mirror part of the device which is surrounded by the fission mantle [7]. The calculations made in that paper indicate that it is possible to achieve an appropriate criticality for the mantle of compact size. The toroidal plasma confinement in such a device depends on whether the magnetic surfaces exist in it. The study made in Ref. 8 shows that under certain conditions the nested magnetic surfaces could be created in a stellarator-mirror machine. The DRACON magnetic trap [9] can be also used for plasma and hot tritium ions confinement.

CALCULATION MODEL

The model is cylindrically symmetric and has a horizontal axis (see Ref. 8). Its radial and axial structure is shown in Fig. 3. The reactor has an axial opening that contains vacuum chamber with D-T plasmas which supplies the fusion neutrons.

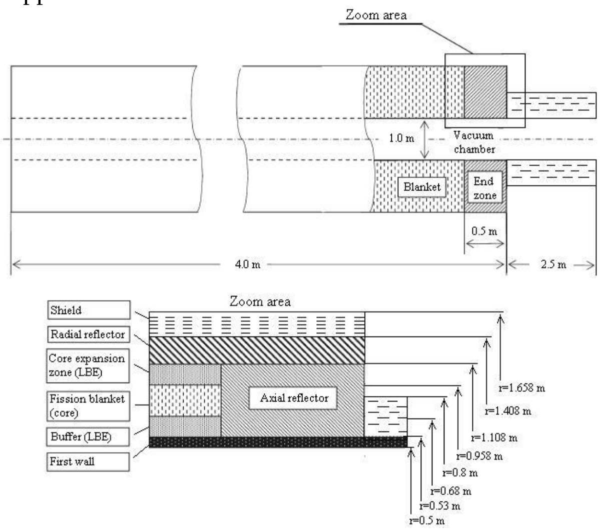

Fig. 3. Radial and axial structures of the mirror based fusion-fission hybrid model

The inner radius of the vacuum chamber is 0.5 m. For the first wall a thickness of 3 cm was chosen. The first wall is made of HT-9 steel [10].

The thickness was determined from the results of critically calculations. The reactor core thickness of 27.8 cm was chosen to make the effective multiplication factor k_{eff}≈0.95. The length of the core is 3 m. It has axial reflectors on both sides. The radial reflector in the model is a homogeneous mixture of HT-9 steel and Li-17Pb-83 (20 % enriched Li-6) with the volume fractions 70 % and 30 %, respectively. This mixture is used for tritium breeding: from the reaction ^{6}Li(n,α)T.

The shield contains a 60:40 vol% mixture of the stainless steel alloy S30467 type 304B7 [11] with water. The steel contains 1.75 wt. % of natural boron. To create a magnetic configuration of the stellarator-mirror machine superconducting magnets will be used. Heating the superconducting magnets by neutrons results in huge energy losses. Therefore, a shield is used to reduce the neutron and gamma loads of them. The shield thickness is of 25 cm. All the materials, as well as their temperatures, which are included in the design were taken from Ref. 12.

The active zone of the reactor is represented in the model as a homogenized mixture of fuel, structure/cladding and coolant. HT-9 and the lead and bismuth eutectic (LBE) were used as structure/cladding and coolant materials, respectively.

The actual fuel material is the zirconium alloy (TRU-10Zr) which consists of the transuranic elements, as shown at the Table 1, with 10 wt.% of zirconium [13]. The alloy has a mass density of 18.37 g/cm^3. A core volume of 4.3 m^3 contains about 5 tones of transuranic elements.

The isotopic composition shown in Table 1 is typical for the composition of the spent nuclear fuel from PWRs after the removal of uranium and fission products. The following volume fraction was used for the homogenized fission blanket: fuel slug material – 0.14, structure/cladding – 0.103, coolant – 0.695. In this study, a specific fuel form was not considered. The LBE was assumed to be a mixture of 44.5 wt.% lead and 55.5 wt.% bismuth. The following material has been used for the axial reflectors: a homogeneous mixture of HT-9 steel and LBE-coolant with the volume fractions 70 and 30 %, respectively.

Table 1

Isotopic composition of the TRU

Element	Composition, wt.%
U-235	0.0039
U-236	0.0018
U-238	0.4234
Np-237	4.313
Pu-239	53.901
Pu-240	21.231
Pu-241	3.870
Pu-242	4.677
Am-241	9.184
Am-242m	0.0067
Am-243	1.021
Cm-243	0.0018
Cm-244	0.1158
Cm-245	0.0125
Cm-246	0.0010

The total length of the main part of the model is 4 m. Since the fusion neutron generation zone extends slightly beyond the fission reactor core, as shown in Fig. 3, and the fission neutrons also leak out here through the axial opening, there is a need to prevent leakage of these neutrons. To arrange that, this part of the plasma column is surrounded by a vessel filled with borated water [14].

The concentration of boron in the water was taken 10 g/kg. The isotopic content is B_{10} – 20 % and B_{11} – 80 %. The part with borated water has a length of 2.5 m at both sides of the main part and a thickness is of 27 cm.

In the calculation model, a D-T fusion neutron source was used. In the model, the neutron emission density was distributed within a number of cylindrical volumes of radius 10 cm and with a length of 4 m. At every source point, the fusion neutrons were emitted with a fixed kinetic energy of 14.1 MeV and isotropic velocity distribution.

Structure of the reactor is illustrated in Fig. 4.

The relative intensity distribution along the length of the neutron source used in the MCNPX model is taken from Ref. 15.

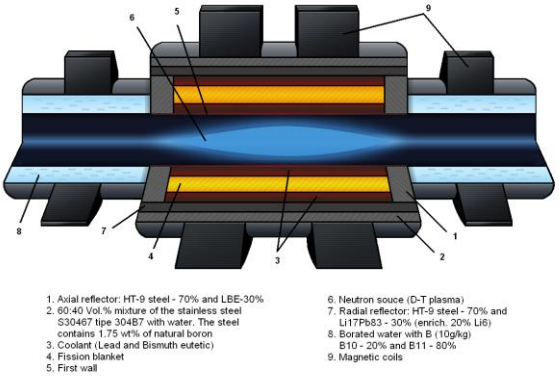

Fig. 4. Scheme of the reactor part of the fusion-fission hybrid

RESULTS OF CALCULATIONS

The MCNPX code [16] has been used to model the neutron transport of the stellarator-mirror fusion-fission reactor.

For the calculation for described above model, the average fission energy deposited in the core per incident source neutron is 1140±1 % MeV. This high number resulted from closeness to unity of the neutron multiplication factor. With neutron generation intensity 6×10^{18} neutrons per second, the fission power is $P_{fis}\approx1100$ MW which corresponds to a power multiplication factor, the ratio of power released to fusion power, of 65.

Fission is the ultimate nuclear reaction concerning the incineration of long-lived fissionable fuel isotopes. Thus, it is of particular interest to know which fission rate has each fissionable isotope as well as the possibility of further usage of fuel unloaded from the hybrid. The MCNPX is calculating a reaction rate following the formula:

$$R = N\cdot\int\varphi(E)\sigma(E)dE,$$

where $\varphi(E)$ is the energy-dependent fluence per one source neutron (cm^{-2}), $\sigma(E)$ is the energy-dependent microscopic reaction cross section (barn), N is the atomic density of material ($atoms\cdot cm^{-3}$).

Table 2

Burnout of the TRU per one fuel cycle

Element	BOC*, wt.%	Burnup, wt.%	EOC**, wt.%
Np-237	4.313	-7.97	3.97
Pu-239	53.901	-10	48.519
Pu-240	21.231	-1.25	20.966
Pu-241	3.870	-2	3.7926
Pu-242	4.677	-2.26	4.57
Am-241	9.184	-8.64	8.39
Am-243	1.021	-7.8	0.94
Cm-244	0.1158	-5.7	0.1092

*BOC – begin of fuel cycle
**EOC – end of fuel cycle

In Ref. 17 burnout rate of transuranics was calculated. In table 2 is shown burning rate of actinides per one fuel cycle. Duration of the single-time fuel usage we determine by Pu-239 burnout which is taken as 10%. It should be noted, that in the calculation only those transuranic elements were taken into account, which together constitute about 99 % of the mass.
U-235, U-236, U-238, Am-242m, Cm-243, Cm-245 and Cm-246 are neglected, but in the calculations of the fuel composition they are included (see Table1).

Table 2 shows that burnup is fast for elements such as Np-237, Pu-239, Am-241, Am-243 and Cm-244. 10 % of plutonium will burn for 125 days. This is an ideal case, since it was assumed constancy of the neutron spectrum in time without taking into account the spectrum distortion with accumulation of fission products.

Table 3

Amount of the TRU

Element	BOC, kg	EOC, kg
Np-237	236	217.2
Pu-239	2900	2610
Pu-240	1135	1120.8
Pu-241	208	203.84
Pu-242	249	243.37
Am-241	336	306.97
Am-243	36	33.2
Cm-244	4.2	3.96

The Table 3 displays the amount of transuranic actinides at the beginning and the end of the first TRU fuel load into the hybrid. The calculation also showed that the neutron multiplication factor by the end of the first TRU fuel load drops to the value of 0.9 and the fission power release falls to 450 MeV per one source neutron due to decrease of the TRU amount.

Further calculations show that the fuel is unloaded from the hybrid reactor after exposure and re-fabrication (removal of fission products) may be reused.

Table 4

Concentration of the TRU

Element	BOC 1, wt.%	BOC 2, wt.%
Np-237	4.313	4.277
Pu-239	53.901	52.2778
Pu-240	21.231	22.587
Pu-241	3.870	4.086
Pu-242	4.677	4.924
Am-241	9.184	9.04
Am-243	1.021	1.013
Cm-244	0.1158	0.117

The Table 4 illustrates a comparison of the concentration of transuranic elements in the first and the second fuel loads. Neutron multiplication factor for the second TRU fuel load will be equal 0.9415 which is only slightly less than the initial k_{eff} value, 0.95.

CONCLUSIONS

Since each TRU fuel load into a hybrid reactor, insufficient amount of transuranic elements is burned. Therefore, to achieve full TRU burnup, the spent TRU nuclear fuel after a first load should be used again. In this case spent TRU nuclear fuel should be placed in a spent fuel pool for a certain time for initial decrease of its radioactivity and power release, after which re-fabrication will be made with removal of the fission products. Then the new TRU fuel should be manufactured and downloaded into the core again. In this instance, while the total mass of the fuel loading remains the same, but the content of transuranic elements will be different. Anyway, the reactivity of the system does not change substantially. It should be noted, that this scenario of handling the spent nuclear fuel makes the nuclear fuel cycle closed.

Another option of the fuel cycle which is not considered here is to make a new fuel by adding minor actinides from spent nuclear fuel instead of burned.

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ТОПЛИВНЫЙ ЦИКЛ ДЛЯ ВЫЖИГАНИЯ МИНОРНЫХ АКТИНИДОВ В ГИБРИДНОМ РЕАКТОРЕ НА ОСНОВЕ СТЕЛЛАРАТОРА СО ВСТРОЕННОЙ ОТКРЫТОЙ ЛОВУШКОЙ

С.В. Черницкий, В.Е. Моисеенко, О. Агрен, К. Ноак

С использованием Монте-Карловского кода MCNPX разработана модель гибридного реактора на основе комбинации стелларатора и открытой ловушки для трансмутации трансурановых изотопов из отработавшего ядерного топлива. Исследуется и обсуждается топливный цикл для подкритического гибридного реактора.

ПАЛИВНИЙ ЦИКЛ ДЛЯ ВИГОРАННЯ МІНОРНИХ АКТИНІДІВ У ГІБРИДНОМУ РЕАКТОРІ НА ОСНОВІ СТЕЛАРАТОРА ТА ВІДКРИТОЇ ПАСТКИ

С.В. Черніцький, В.Є. Моісеєнко, О. Агрен, К. Ноак

За допомогою Монте-Карлівського коду MCNPX розроблена модель гібридного ректора на основі комбінації стеларатора та відкритої пастки для трансмутації трансуранових ізотопів з відпрацьованого ядерного палива. Досліджується та обговорюється паливний цикл для підкритичного гібридного реактора.