MINOR ACTINIDES BURNING IN A STELLARATOR-MIRROR FUSION-FISSION HYBRID

S.V. Chernitskiy [1]***, V.E. Moiseenko***[2]***, O. Ågren*** [3]***, K. Noack*** [3]

[1] ***"Nuclear Fuel Cycle" Science and Technology Establishment NSC***
''Kharkov Institute of Physics and Technology", Kharkov, Ukraine;
[2]***Institute of Plasma Physics of the NSC ''Kharkov Institute of Physics and Technology",***
Kharkov, Ukraine;
[3]***Uppsala University, Ångström Laboratory, Uppsala, Sweden***

The MCNPX Monte-Carlo code has been used to model a compact concept of a fusion-fission reactor based on a combined stellarator-mirror trap for transmutation transuranic elements from the spent nuclear fuel. Calculation results for fission rates for transuranic elements are presented.

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INTRODUCTION

Utilization of spent nuclear fuel is an actual global problem. Storing it in geological nuclear waste repositories is not a sustainable solution. Because of the slow decrease of radioactivity, the repository term is incredibly long, about 300.000 years [1]. The long-term radiotoxicity of waste (Fig. 1) is clearly dominated by actinides. An option for geological storage is separation of transuranic elements and burning them in fast reactors. The waste without transuranic content becomes non-radioactive much faster.

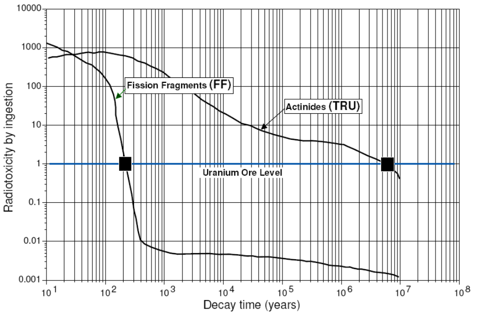

Fig. 1.Time evolution of the potential radiotoxicity (relative to uranium ore) of the two main components of nuclear waste for PWR spent fuel

Fuel with transuranic elements could be burned in a fast reactor, but has a deficit in delayed neutrons, which decrease the reactor controllability [2, 3]. Fast reactors with liquid metal coolant (for example Na) have a positive void effect of reactivity, which is also a drawback of the reactors from the point of view of nuclear safety. Besides reducing the value of the Doppler-effect at the fast reactors, unlike pressurized water reactors (PWR), leading to deterioration of nuclear safety in the case of accident situations, such as an increase the temperature of the fuel in the reactor. Thus, an attractive idea is the development of a subcritical reactor, the main purpose of which will be a safe burning of transuranic elements from the spent nuclear fuel. The sub-critical reactors which are controlled by an external neutron source are more costly, but have certain advantages before critical reactors. Together with efficient power production they offer an improved controllability of the chain fission reaction that boosts reactor safety.

STELLARATOR-MIRROR HYBRID

In Ref. 4 a stellarator-mirror hybrid reactor (Fig. 2) is proposed. 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.

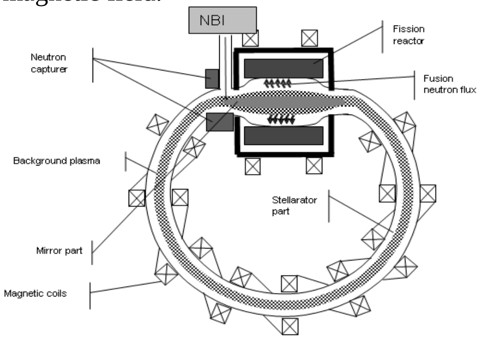

Fig. 2. Sketch of the fission-fusion hybrid

The stellarator part provides confinement of warm dense deuterium target plasma. Hot sloshing tritium ions are confined at the mirror part of the device. At this part the plasma column is straight. The hot minority tritium ions are sustained in the plasma by the neutral beam injection (NBI). The NBI is normal to the magnetic field and targets plasma just near the fission mantle border. The sloshing ions bounce inside the magnetic mirror between the injection point and mirror point where the magnetic field has the same value as the in injection point. The toroidal plasma confinement in such a device depends on whether the magnetic surfaces exist in it. The study made in Ref. 5 shows that under certain conditions the nested magnetic surfaces could be created in a stellarator-mirror machine.

The embedded magnetic mirror is surrounded by a cylindrically symmetrical fission mantle described in Ref. 6. The calculations made in that paper indicate that it is possible to achieve an appropriate criticality for the mantle of compact size.

CALCULATION MODEL

The model is cylindrically symmetric and has a horizontal axis (see Ref. 6). Its radial and axial structure is shown in Fig. 3. The reactor has an axial opening that

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contains vacuum chamber with D-T plasmas which supplies the fusion neutrons.

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 [7].

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 Li17Pb83 (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 [8] with water. The steel contains 1.75 wt.% of natural boron. A shield is used to reduce the neutron and gamma loads of the stellarator-mirror magnetic coils needed for the plasma confinement. 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. 9.

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 [10]. 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. 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.

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 [11].

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.

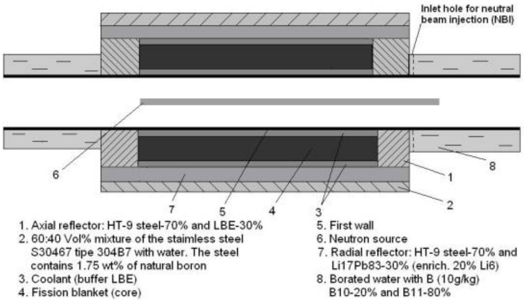
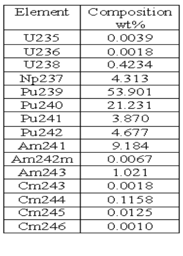


Fig. 4. Scheme of the reactor part of the fusion -fission hybrid

At the right side of the reactor, openings are made to provide access to the plasma for the neutral beam (Fig. 4, inlet hole for neutral beam injection).

In the calculation model, a D-T fusion neutron source was used. The 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.

Table 1. Isotopic composition of the TRU



Element	Composition wt%
U235	0.0039
U236	0.0018
U238	0.4234
Np237	4.313
Pu239	53.901
Pu240	21.231
Pu241	3.870
Pu242	4.677
Am241	9.184
Am242m	0.0067
Am243	1.021
Cm243	0.0018
Cm244	0.1158
Cm245	0.0125
Cm246	0.0010

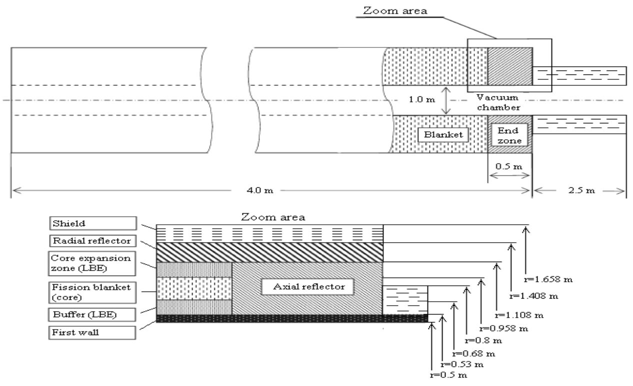


Fig. 3. Radial and axial structures of the mirror based fusion-fission hybrid model

The relative intensity distribution along the length of the neutron source used in the MCNPX model is taken from Ref. 12. The total fusion power is 17 MW.

RESULTS OF CALCULATIONS

The MCNPX code [13] 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 1200±1% MeV. This high number resulted from closeness to unity of the neutron multiplication factor. With neutron generation intensity $6 \cdot 10^{18}$ neutrons per second, the fission power is P_{fis}≈1100 MW which corresponds to a power multiplication factor, the ratio of power released to fusion power, of 65.

Besides, a calculation with sodium coolant that may be used instead of LBE coolant is performed. For comparison, calculation results for the total energy, deposited in the core per one source neutron, with LBE and sodium coolants are presented at the Table 2.

Table 2. The fission energy, deposited in the core per one source neutron

Coolant LBE	Coolant Na
1200 MeV	1160 MeV

It should be noted that in the model with usage of sodium coolant, the volume of the active zone was significantly increased in the radial direction in order to provide k_{eff} ~0.95. For this case, a core volume of 15 m^3 contains about 18 tones of transuranic elements. The Table 2 prompts that total power of the installation remains almost the same.

The spectrum of the neutron flux is important for burnup and transmutation of the fuel. Fig. 5 shows the energy group fluxes (neutron flux integrated over energy intervals) per one fusion neutron averaged over the active zone of the reactor. The statistical errors are around 1% for all the results presented below.

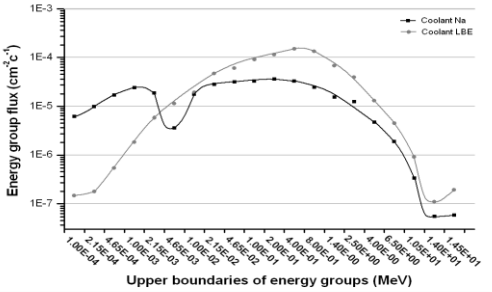


Fig. 5. Averaged energy group fluxes

Fig. 5 also indicates that fusion neutrons in the core are in minority, while the major part of the spectrum represents the fission spectrum. Furthermore, in the spectrum of neutrons with the sodium coolant, a substantial portion of low-energy neutrons is present.

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. 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 ($atoms \cdot barn^{-1} \cdot cm^{-1}$).

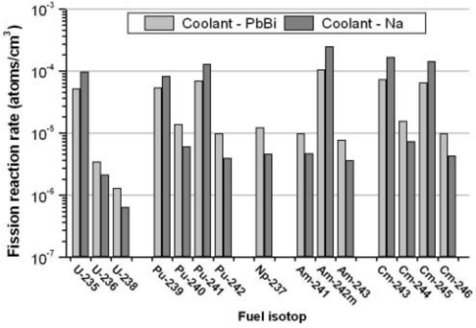


Fig. 6. Fission rates of fuel isotopes per fusion neutron and per nucleus

The diagram of Fig. 6 displays the calculated fission reaction rates for isotopes contained in the fuel of the present fusion-fission hybrid. The represented quantity is the average number of fission reactions produced per fusion source neutron and per nucleus considered. The diagram indicates that the well fissionable isotopes ^{235}U, ^{239}Pu, ^{241}Pu, ^{242m}Am, ^{243}Cm and ^{245}Cm have the highest fission rates, whereas the hardly fissionable isotopes have fission rates about one order of magnitude less.

The diagram of Fig. 7 illustrates the calculated average number of fission reactions produced per one fusion neutron given concentration of the TRU in the fuel.

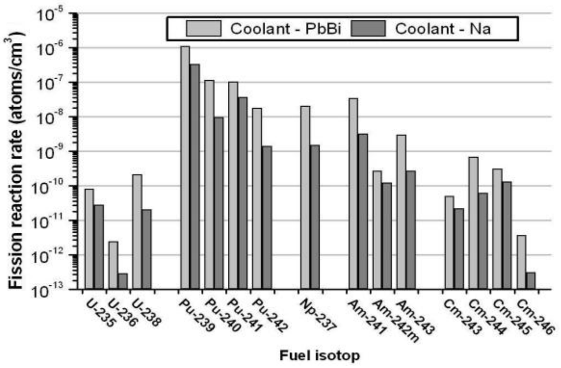


Fig. 7. Fission rates of fuel isotopes per fusion neutron

The diagram demonstrates that the burning of transuranics per cm^3 much better in case coolant LBE because the density of the material per unit volume varies for different coolants.

Calculation results for the burnup of the TRU are presented below. In the calculations for each isotope accounts a decrease in its amount due to the reactions of fission and neutron capture, as well as an increase due to the neutron capture reaction and beta decay of the neighbouring isotopes.

$$\frac{dN({}^{A}_{Z}M)}{dt} = -\phi\sigma_f({}^{A}_{Z}M)N({}^{A}_{Z}M) - \phi\sigma_c({}^{A}_{Z}M)N({}^{A}_{Z}M) +$$

$$+\phi\sigma_c({}^{A-1}_{Z}M)N({}^{A-1}_{Z}M).$$

Table 3. Burning TRU per year

Isotope	Burnup	
	coolant – LBE	coolant – Na
U-235	-17 %	-6 %
U-236	+3.5 %	+2 %
U-238	-2.3 %	-2 %
Pu-239	-14.3 %	-6 %
Pu-240	-1.5 %	+3 %
Pu-241	-3.2 %	+4.4 %
Pu-242	-3.2 %	-0.5 %
Np-237	-11 %	-5.3 %
Am-241	-17 %	-8 %
Am-242m	+100 %	+100 %
Am-243	-15 %	-7.7 %
Cm-243	-28 %	-12.7 %
Cm-244	-12 %	-4.3 %
Cm-245	+40 %	+25 %
Cm-246	+29 %	+13.7 %

As seen from the results, of the Table 3 rates of burning of minor actinides are suitably high. Increase the amount of some isotopes occurs only for those ones which amount is small.

The Table 4 shows the amount of transuranic, which burns throughout the year for the present fusion-fission hybrids. This value is compared with the amount of TRU produced at the one light water reactor (LWR) per year [14, 15].

Table 4. Composition and quantity of the TRU burning at the hybrid reactor per year

Element	The amount of TRU established at the one LWR reactor per year	Burnup of the TRU at the hybrid reactor with coolant LBE	Burnup of the TRU at the hybrid reactor with coolant Na
Uranium	20.000 kg	-	-
Neptunium	12 kg	13 kg	22 kg
Plutonium	205 kg	220 kg	231 kg
Americium	20 kg	21 kg	23 kg
Curium	0.4 kg	0.16 kg	0.13 kg

One can see that the burnup of the TRU for the hybrid reactor with different coolants almost the same, and also it is close to the amount of TRU produced in one LWR reactor.

CONCLUSIONS

The results of the calculations that were carried out with the Monte Carlo code MCNPX can be summarized as follows:

1. The neutron spectrums in the blanket with using two types of coolant are calculated.
2. Calculation results for the fission reaction rates for transuranic elements are presented.
3. Burnup of the isotopes contained in the fuel of the present fusion-fission hybrid are shown.

The calculations demonstrate that analysed version of the subcritical reactor can provide complete transmutation of TRU. The results of calculations also allow one to make estimates for necessary fleet of such reactors needed to empty nuclear repositories in given term.

One of the opportunities to provide sustainable usage of nuclear energy is simultaneous operation of LWR and hybrids. However in this scheme, each LWR needs one hybrid reactor for transmutation its TRU.

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ВЫГОРАНИЕ МИНОРНЫХ АКТИНИДОВ В ГИБРИДНОМ РЕАКТОРЕ НА ОСНОВЕ СТЕЛЛАРАТОРА И ОТКРЫТОЙ ЛОВУШКИ

С.В. Черницкий, В.Е. Моисеенко, O. Ågren, K. Ноак

С использованием программы MCNPX разработана модель контролированного гибридного реактора небольших размеров на основе открытой ловушки для трансмутации трансурановых изотопов из отработавшего ядерного топлива. Представлены результаты расчетов скорости деления трансурановых элементов.

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

С.В. Черницький, В.Є. Моісеєнко, O. Ågren, K. Ноак

За допомогою програми MCNPX розроблена модель контрольованого гібридного ректора невеликих розмірів на основі відкритої пастки для трансмутації трансуранових ізотопів з відпрацьованого ядерного палива. Представлені результати розрахунків швидкості ділення трансуранових елементів.