Transmutation Potential of Reactor VVER-440

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ABSTRACT

Theoretical evaluation of VVER-440 transmutation potential by HELIOS – code is presented. Transmutation method proposal comprising special transmutation pins, combined FA and simple reprocessing is described. Transmutation efficiency of the method is characterized.

1. INTRODUCTION

Nuclear fuel cycle back-end solution depends on many factors, connected closely with characteristics of the country, developing nuclear energetic. With typical small nuclear economy high level waste consists of burned fuel assembly (FA) and some other materials from NPP operation. There is no problem with military abuse of Pu. Economy power usually does not allow to develop individually some revolutionary back end solutions as ADTT. Transmutation of spent fuel should be connected with as simply reprocessing (partitioning) technology as possible in order to facilitate method development and implementation.

2. BACK-END SOLUTIONS FOR SMALL NUCLEAR ECONOMY

Two basic solutions are usually taken into account in small nuclear economy with reactors VVER-440. Various criteria – mainly economic and technical – can be used for selection. Usual solutions are as follows:

- Deep geological disposal of irradiated fuel without reprocessing - the least expensive solution with the least handling, - U and Pu mines are created
- Payment for permanent spent fuel disposal in another country (Russia) – questionable solution as future burned of FA's is not clear.

REPU or MOX FA have preparation not been usual alternatives up to now. Because of reasons mentioned earlier revolutionary transmutation technologies can be developed in close cooperation with more powerful and ambitious countries. Evolutionary transmutation technology with solid fuel in VVER-440 reactors can be of greater interest and is discussed in the next chapters. Closure of nuclear fuel cycle from the point of view of transuranium elements should be the most important result, that can solve non-proliferation problems of Pu generated during VVER-440 exploitation.

3. TRANSMUTATION WITH SOLID FUEL

(VVER-440)

Revolutionary transmutation technologies are based on cores with typical neutron flux densities 10^{15} $cm^{-2}s^{-1}$ and more. Flux densities at PWR (VVER-440) reactors are much lower $\sim 10^{14}$ $cm^{-2}s^{-1}$. But preliminary evaluations [1] showed significant transmutation potential of such cores in the case, when materials for transmutation stay in the core for a long time.

3.1 COMBINED FUEL ASSEMBLY

Transmutation with pressure – water reactors with hexagonal FA - reactor type VVER-440 - was taken into account. Modification of standard FA was designed to facilitate transmutation with solid fuel. Modification is performed by replacement of 6 corner fuel pins in the standard FA by so called transmutation pins (T-pins). All other pins are standard - uranium ones (U-pins) with the same "basic" enrichment. FA after the modification is called combined fuel assembly (CFA) – see Fig. 1.

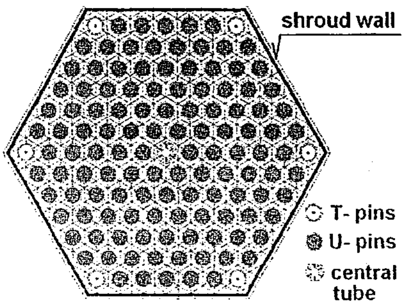

Fig. 1 Combined fuel assembly

A simplified preparation of T-pin is suggested as follows:

- FA is burned up to 40 MWd/kgU and cooled for 5 years;
- uranium is removed completely from the burned fuel;
- transuranium elements in the rest are oxidised (dioxides XO_2 are supposed, X- transuranium element);
- resultant material is transformed into the fuel pellets with the same density and dimensions as fresh fuel one has;
- T-pins are filled by prepared non-uranium pellets;
- all dimensions and materials (except fuel pellets) are identical with standard VVER-440 FA.

3.2 EQUILIBRIUM FUEL CYCLE OF COMBINED ASSEMBLY

Burn-up and cooling of standard FA and CFA was modelled by spectral code HELIOS [2]. Burn-up of FA was calculated as first cycle of the fuel. FA enrichment was the same in all pins and was identical with basic enrichment in the following CFA. CFA prepared on the basis of burned fuel from the previous cycle was used with all consequent cycles. Two ways of CFA preparation were taken into account:

1) burned uranium from U-pins of CFA was used for T-pin pellets preparation ⇒ CFA1
2) burned material from all pins at CFA (U-pins and T-pins) was used for T-pin pellets preparation ⇒ CFA2

Described process was repeated many times and equilibrium fuel cycles EFC1 (with CFA1) and EFC2 (with CFA2) were received. The EFC2 can serve as ideal (maximal) transmutation possibility.

First calculations of CFA's were performed with basic enrichment of U-pins 3,6 $\%^{235}U$. But multiplication ability of such CFA is low – see CFA2 with basic enrichment 3,6% at Fig. 2.

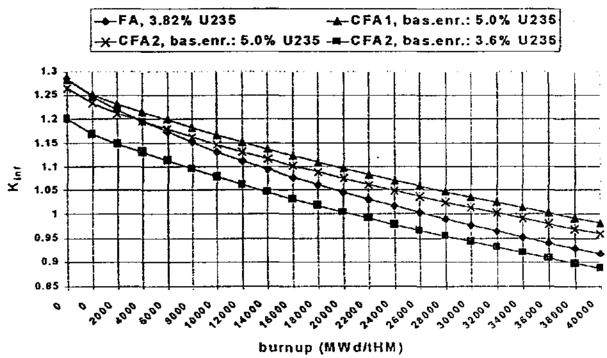

Fig.2 Comparison of infinite multiplication factor K_{inf} at varios equilibrium CFA cycles and with open FA cycle

In order to compensate for the negative reactivity influence of T-pins basic enrichment was increased up to 5 %^{235}U. Results of equilibrium fuel cycle calculation can be seen in Fig. 3÷10.

Sequential numbers mark the position of CFA in EFC. Number 0 marks values of standard FA (values for the whole FA).

Cs137 was selected as an example of fission product behaviour in EFC1 and EFC2 – see Fig. 3 and Fig. 4.

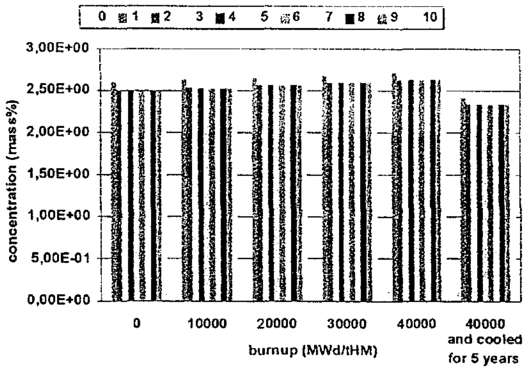

Fig.3 Cs137 concentration with EFC1 - T-pin of CFA1

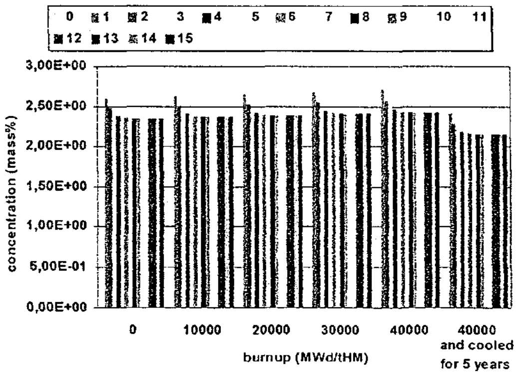

Fig.4 Cs137 concentration with EFC2 - T-pin of CFA2

Remarkable concentration increase in T-pins can bee seen during burn-up while small decrease is characteristic going through the EFC. But tendencies are different for various fission products.

Concentration behaviour of Pu239 as very important transuranium element can be seen on Fig.5 and 6.

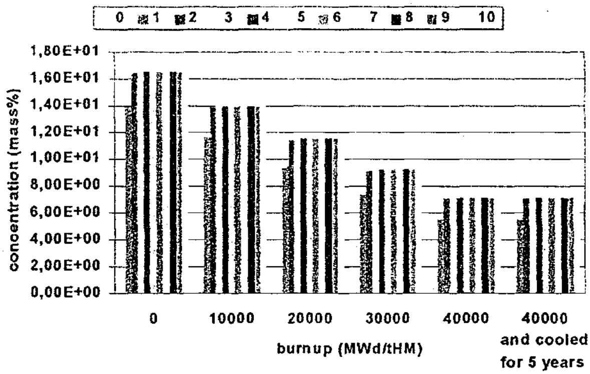

Fig.5 Pu239 concentracion with EFC1 - T-pin of CFA1

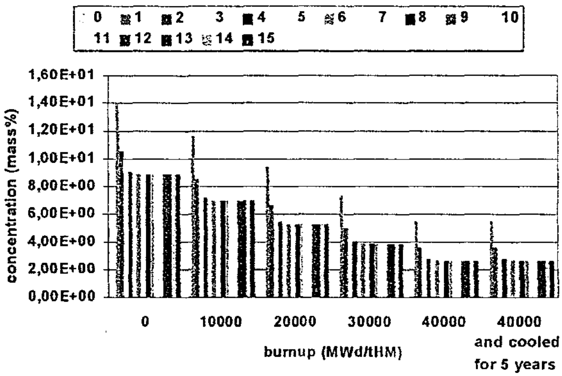

Fig.6 Pu239 concentration with EFC2 - T-pin of CFA2

Significant decrease with burn-up as well as with sequential number can be seen. Both tendencies are just opposite for Cm246 – last transuranium element at HELIOS library – see Fig. 7 and 8.

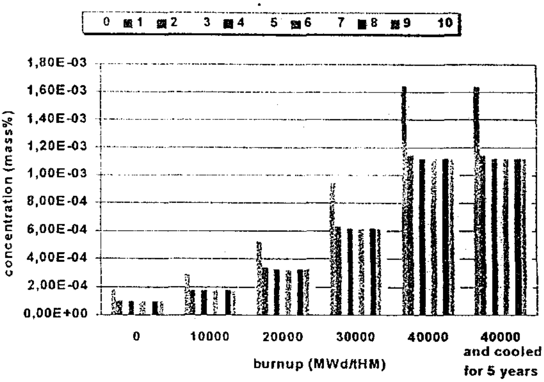

Fig.7 Cm246 concentration with EFC1 - T-pin of CFA1

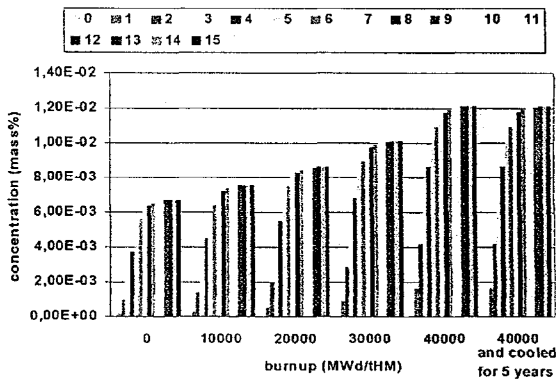

Fig.8 Cm246 concentration with EFC2 - T-pin of CFA2

Various tendencies can be observed for various transuranium elements. In general – sequence number dependencies are more significant and equilibrium is reached later with EFC2.

Infinite multiplication coefficient changes can be seen on Fig. 9 and 10. Equilibrium values are reached quickly at both cycles.

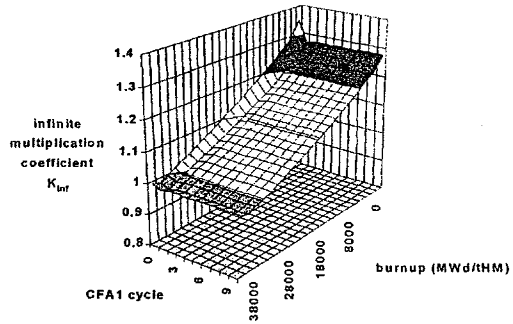

Fig.9 Infinite multiplication coefficient K_{inf} with EFC1

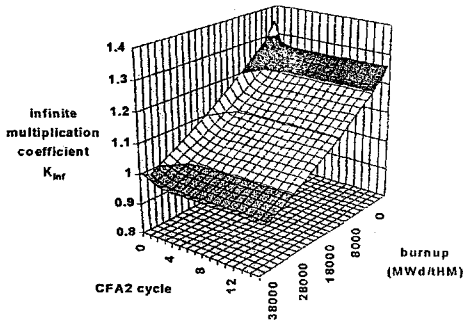

Fig.10 Infinite multiplication coefficient K_{inf} with EFC2

Designed equilibrium fuel cycles can be considered as realistic ones, if ability of the core to burn CFA's up to 40 MWd/kgU (burn-up reactivity reserve high enough) is proven. Comparison of infinite multiplication coefficient K_{inf} for standard VVER-440 FA with enrichment 3,82 % and CFA1 and CFA2 with basic enrichment 5 % can be seen on Fig. 2. K_{inf} values of CFA1 and FA 3,82 % are almost the same at zero burn-up, CFA2 values are slightly lower. But as decrease of CFA curves is slower in comparison with FA 3,82 % one, CFA K_{inf} values are higher for most burn-up values (CFA2 starting from 5 MWd/kgU). It means that as a first approximation standard FA with enrichment 3,82 % can be assumed equivalent (with some reserve) with mentioned CFA from the point of view of fission ability. Natural uranium utilisation as a function of enrichment and other parameters can be seen [3] on Fig. 11.

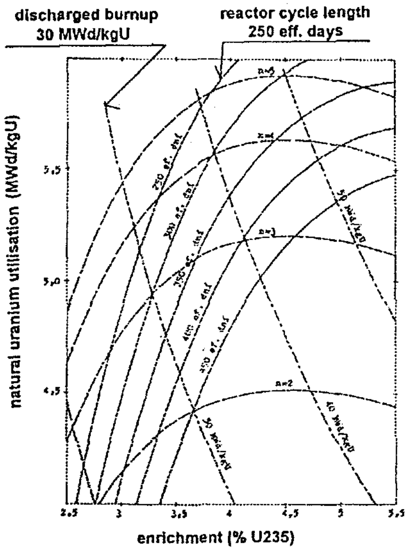

Fig.11 Natural uranium utilisation at VVER-440 reactors as a function of enrichment and refueling interval (low leakage cores)
n - number of reactors cycles in the assembly cycle

Common point of two curves: n=4 (four reactor cycles create one fuel assembly cycle) and 40 MWd/kgU (discharged burn-up) is important for comparison with CFA's (reactor cycle length is 300 eff. days). Enrichment value 3,88 can be seen as appropriate for fuel burning up to 40 MWd/kgU in 4-year fuel cycle (n=4). Fig. 11 was prepared for older VVER-440 FA's with higher parasitic absorption (Fe-spacer grids, higher shroud wall thickness,....). Lower enrichment of recent FA's can be supposed to reach desired burn-up 40 MWd/kgU. It means that at first guess the basic enrichment 5 %U235 is enough to reach CFA burn-up 40 MWd/kgU in real VVER-440 reactor.

3.3 CFA TRANSMUTATION EFFICIENCY

Table I.
Masses [kg] of selected fission products and transuranium elements in discharged fuel (FA – the whole FA, CFA – 6 T-pins)

	Sr90	Zr93	Tc99	I129	Cs137
FA, 3.6 % U235	6.64E-02	9.93E-02	1.11E-01	2.27E-02	1.55E-01
FA, 5.0 % U235	7.26E-02	1.05E-01	1.13E-01	2.12E-02	1.55E-01
CFA1, bas. enr.: 5,0 % U235	6.61E-02	1.15E-01	1.21E-01	2.49E-02	1.52E-01
CFA2, bas. enr.: 5,0 % U235	5.76E-02	1.19E-01	1.18E-01	2.65E-02	1.40E-01

	Np237	Pu238	Pu239	Pu240	Pu241
FA, 3.6 % U235	6.65E-02	2.63E-02	7.58E-01	2.99E-01	1.50E-01
FA, 5.0 % U235	7.08E-02	2.33E-02	8.39E-01	2.64E-01	1.41E-01
FA1, bas. enr.: 5,0 % U235	4.92E-02	5.98E-02	4.63E-01	3.35E-01	1.17E-01
CFA2, bas. enr.: 5,0 % U235	3.12E-02	7.40E-02	1.70E-01	2.44E-01	8.87E-02

	Pu242	Am241	Am243	Cm244	Cm246
FA, 3.6 % U235	7.11E-02	4.64E-02	1.65E-02	5.01E-03	3.46E-05
FA, 5.0 % U235	4.71E-02	4.40E-02	9.74E-03	2.43E-03	1.11E-05
CFA1, bas. enr.: 5,0 % U235	6.52E-02	6.74E-02	1.63E-02	6.40E-03	7.28E-05
CFA2, bas. enr.: 5,0 % U235	9.39E-02	5.07E-02	2.41E-02	1.44E-02	7.86E-04

Comparison of resulting masses of selected "unpleasant" fission products and transuranium elements can be seen in Table I. Values for open fuel cycle and for EFC1 an EFC2 are given. Values in [kg] are given for the whole standard FA with open fuel cycle and for 6 T-pins in the case of CFA1 and CFA2. High reduction of Pu239 concentration in equilibrium fuel cycles (almost 5-times with EFC2) is the most important change for transuranium elements. Changes are small for fission products.

New reactor types, connected with back-end revolutionary solution – for instance molten salt reactors [4,5] have an ambition to close fully the fuel cycle of minor actinides and to minimise the amount of long-lived radwastes. Burning potential is based on neutron flux densities ~10^{15} $cm^{-2}s^{-1}$.

Material flow connected with EFC1 can be seen on Fig. 12.

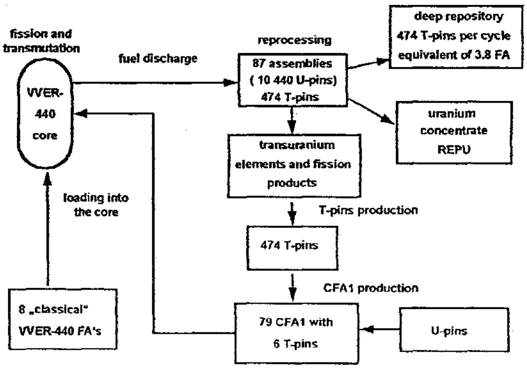

Fig.12 Equilibrium fuel cycle EFC1 - material flow

Four-year fuel cycle of VVER-440 reactor is supposed. As the core comprises 349 assemblies, 87 of them are replaced during each refuelling (central FA is not taken into account). Mass fraction of fission products and transuranium elements with U-pins is about 4 %. After reprocessing (uranium removing) of U-pins 474 T-pins and consequently 79 CFA1 assemblies are produced. It means, that 8 standard FA must be added during refuelling in order to fill all positions in the core.

All T-pins of one fuel batch (474 pieces) are removed after 4-years in the core and placed into the deep repository. This T-pin amount creates equivalent of less than 4 assemblies. In comparison with open fuel cycle (87 FA's), the material flow into the deep repository is more than 20-times smaller.

4. CONCLUSION

Back-end solutions for small nuclear economy based on VVER-440 reactors have been reviewed with transmutation as reasonable non-proliferation measure. Evolutionary back-end solution-transmutation methodology with solid fuel of VVER-440 reactors has been described. Special transmutation fuel pins and combined fuel assemblies - have been characterised. Calculation analysis results of two transmutation equilibrium fuel cycles by spectral code HELIOS have been presented. First was realistic one and second one serves as model of ideal transmutation in VVER-440 core. Reactivity reserve high enough to burn combined fuel assemblies up to supposed 40 MWd/kgU is proven based on comparison with standard VVER-440 FA with mean enrichment 3,82 % U235.

Significant transmutation efficiency (e.g. multiple reduction of Pu239 amount) of VVER-440 core has been shown as well as reduction (division) of material flow into the deep repository by factor more than 20 by suggested transmutation methodology.

As transmutation ability of VVER-440 core is not negligible, more detailed analyses of the method by fuel management and other codes seems to be reasonable.

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