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PARTIALLY CLOSED FUEL CYCLE OF VVER-440

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ABSTRACT

Position of nuclear energy at the energy sources competition is characterised briefly. Multi-tier transmutation system is outlined out as effective back-end solution and consequently as factor that can increase nuclear energy competitiveness. LWR and equivalent VVER are suggested as a first tier reactors. Partially closed fuel cycle with combined fuel assemblies is briefed. Main back-end effects are characterised.

1. INTRODUCTION

Consumption of electricity in Europe is supposed to grow at least at the horizon 20 years [1]. Report „European electricity market outlook" of Finish Energy Industries Federation Finergy shows, that electricity consumption grows faster in comparison with production. As a consequence more and more countries will have to resort to increasing energy import. Concerning EU, 200 000 to 300 000 MW of new electricity supply capacity will be required within the next 20 years and equally as much is needed to compensate production capacity which becomes retired. Fast electricity consumption growth is supposed in Russia and Baltic countries after structural transition of economy. Concerning nuclear power (and coal) there are intentions on one hand to reduce (Germany) and on the other hand to increase (Russia) their use. Position of nuclear energy in the competition of energy sources is supported by restriction in carbon dioxide emissions as EU members and some other states ratified the Kyoto Protocol.

Concerning greenhouse effect reduction, EFN association [2] suggested several kind of actions as energy waste reduction, renewable sources development or CO_2 emission credits market support and stresses key role of Nuclear energy in environment friendly electricity production.

"Ecological" nuclear energy production has good changes to cover growing electricity demands. Main environmental problem connected with nuclear energy exploitation is spent fuel management, discharged annually from some 400 commercial nuclear power plants now in operation.

The management of spent fuel should ensure that the biosphere is protected under economically acceptable conditions without entailing unfavourable short-term consequences and the public must be convinced of the effectiveness of the methods. Since the spent fuel contains very long-lived radio-nuclides some protection is required for at least 100 000 years. Two ways are possible:

- waiting for the natural decay of the radioactive elements isolated physically from the biosphere by installing successive barriers at a suitable depth in the ground. This strategy leads to deep geological disposal;
- exploitation of nuclear reactions that will transmute the very long-lived wastes into less radioactive or shorter-lived products.

2. MULTI-TIER TRANSMUTATION

Believed as the most effective transmutation means are Accelerator Driven Systems (ADS) that can supply high enough neutron densities for sufficient transmutation efficiency. But because this revolutionary technology needs decades of expensive research and development, reactor types and concepts in exploitation or under development are also taken into account in connection with at least partial transmutation. Such evolution of nuclear technology can profit from gathered experience and is likely to be cheaper in comparison with ADS. Multi-tier transmutation system [3] is natural combination of mentioned approaches. Performs combination of transmutation effects as follows: much of plutonium and perhaps other problematic materials can be consumed in power reactors (Tier 1 with thermal spectrum) and more actinides and fission products can be destroyed at accelerator – based transmutation systems (Tier 2 – fast spectrum). Such complex Multi-tier system can reach objectives as follows:

- to improve long-term public safety by reduction of spent fuel radio-toxicity and future inhabitants peak doses;
- to provide benefits to the repository program by reduction of heat producing material inventory and spent fuel mass and by minimisation of criticality risk;
- to reduce the proliferation risk from plutonium in commercial spent fuel;
- to improve prospects for nuclear power by waste management problem solution.

Thermal-spectrum gas-cooled reactor (GT-MHR) with good transmutation potential [4] can serve as an example of reactor system under development for first tier (or first strata). But partial first tier transmutation can be performed also at existing or new light water reactors (LWR's) [5,6]. Pu, minor actinides and even some long-lived fission products (LLFP) can be burned there partially. This first tier concept can exhibit some advantages for ADS at second tier as minimisation of reactivity swing during ADS cycle by minimisation of Pu content in ADS fuel or reduction of the amount of material sent to the ADS. Exploitation of non-fertile fuel with burnable absorber in LWR's is also taken into account.

Combination of LWR and ADS technology seems to be highly beneficial and should be examined more closely.

3. VVER-440 TRANSMUTATION APPLICATION

LWR reactors in general were mentioned in previous chapter. VVER reactor, that are in exploitation in Russia and some other countries in Europe (and Asia) can be considered as specific type of LWR reactors. Main difference in comparison with LWR is hexagonal shape of FA's and triangular net for FA's and pins.

Back-end solution depends also on economy power of country, solving the problem. At small nuclear economy with high share of nuclear electricity (Slovakia with 5 million people and more than 50 % electricity form six VVER-440 reactors is typical example) high level waste consists of burned FA's and some other materials from NPP operation (no problems with military abuse of Pu). Partitioning and transmutation is contemporary progressive back-end solution. But economical potential does not allow to develop individually some revolutionary back-end technology as ADS. Selected method should be as simple as possible in order to facilitate its development and implementation. The only realistic way is to participate on international development effort and explore existing equipment and experience.

Reactor VVER-440 was taken into account as safe, reliable and long time exploited candidate for first tier reactor and very simple separation process was supposed at the first stage. Resulting transmutation fuel cycle of VVER-440 reactor with partially uranium–free (UF) fuel in so called combined fuel assembly (CFA) is described in following paragraphs.

COMBINED FUEL ASSEMBLY DESCRIPTION

CFA is used for transmutation process introduction into the VVER fuel cycle. Several equilibrium fuel cycles with CFA was developed for VVER-440 reactor. Changes of isotopic composition, reactivity and other parameters during burn-up were modelled by Norwegian-Swedish spectral code HELIOS [7].

Combined fuel assembly is a model of the special transmutation fuel assembly. Its purpose is to transmute transuranium elements (TRU) and fission products (FP) (Fig. 1). Geometry of CFA and natural material composition of all parts except fuel pins are the same as in of the original fuel assembly, which is used at the VVER-440 reactor (in following text labelled as VVER fuel assembly or VVER FA).

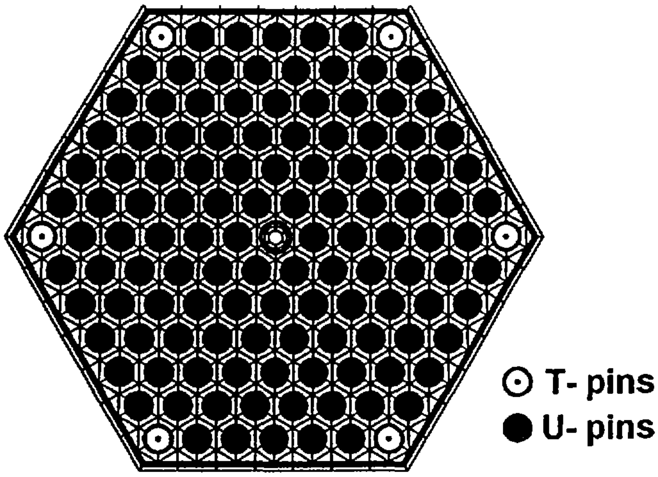

Fig.1 The model of CFA

The only difference between CFA and VVER FA is material composition of fuel pins. There are 126 uranium fuel pins (U-pins or UP) in VVER FA but 120 U-pins and 6 transmutation pins (T-pins or TP) in CFA [8], [9]. TP's contain TRU and FD only, there is no uranium for the reason not to breed another TRU. T-pins are placed at the assembly corners where higher thermal flux speeds up transmutation process. Another advantage is flattening of radial power distribution in CFA.

Composition of CFA U-pins is the same as in VVER FA except for U-235 enrichment, which is 5% of U-235. Goal of higher enrichment is to approach multiplication properties of CFA to ones of VVER FA with the mean enrichment of U-pins 3.82% of U-235. Neutron balance at CFA is deteriorated by high neutron absorption of FP at T-pins. In such a way is possible to reach discharge burn-up 40 MWd/kgHM at 4-year fuel cycle.

5. EQUILIBRIUM FUEL CYCLE OF COMBINED FUEL ASSEMBLY

A way to reach equilibrium fuel cycle (EFC) [10] of CFA is shown on Fig. 2. Fresh CFA or fresh VVER FA (at first cycle) is burned-up to 40 MWd/kgHM in the core of VVER-440 and cooled for 5 years at the reactor pool. Partitioning and transmutation process integrated with fuel cycle can be divided into five stages as follows:

1. Burned U-pins and T-pins are separated (120 U-pins and 6 T-pins from CFA, 126 U-pins only from VVER FA).
2. Uranium is separated from burned U-pins and is manipulated as low level waste (LLW) or can be used as a material for fresh U-pins preparation.
3. TRU and FP - rest of burned U-pins after uranium separation – are concentrated to the T-pins (6 pcs approx. from one assembly) and create fresh CFA together with 120 fresh U-pins.
4. T-pins are not reprocessed, are regarded and manipulated as high level waste (HLW) and wait for second tier. As a main facility for other tiers is considered an accelerator driven system (ADS) or fast breeder

reactor. It should be a facility that uses a fast spectrum of neutrons to reach the maximum transmutation effect.

5. Fresh CFA is loaded into the VVER-440 core, burned-up to 40 MWd/kgU, cooled for 5 years and cycle comes back to the stage 1.

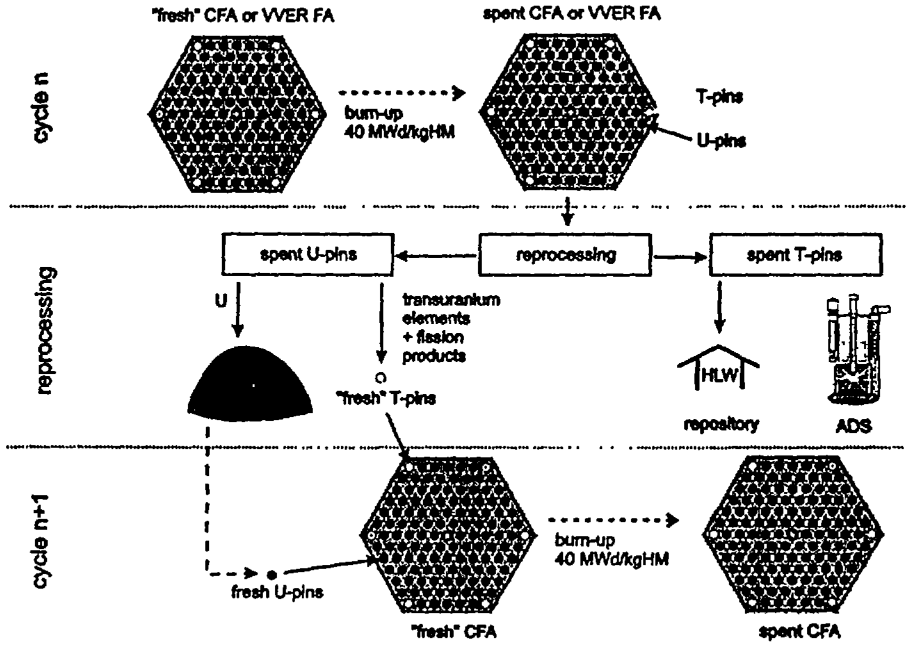

Fig.2 EFC with CFA

Described fuel cycle was done 10-times and then mass concentration of FP and TRU were analysed. On the assembly level the positive effect of this way of transmutation is a general fall of Pu-239 concentration at T-pins. On the other hand, the negative effect is concentration increase of some TRU and FP, for example Cm-246. Quantitative effects on the core level are given in following paragraphs.

6. PARTIALLY CLOSED FUEL CYCLE OF VVER-440

There is an effort to close partially a fuel cycle to limit TRU (and FP partially) production. For this purpose a model of core fuel cycle with CFA was created. The partially closed equilibrium fuel cycle (PCFC) model is shown on Fig. 3. Material flow can be described as follows.

After 40 MWd/kgHM burn-up, 87 fuel assemblies are discharged (13 VVER FA's and 74 CFA's) After U separation FP and TRU from 10 518 U-pins are concentrated (their total mass is 454 kg) and 444 T-pins are fabricated. After 10 518 fresh U-pins were added to 444 fresh T-pins, 74 fresh CFA's are created. By addition of 13 fresh VVER FA's fresh fuel batch is created and loaded into the VVER-440 reactor core. Spent 444 T-pins are moved to storage to wait for second tier of multi-tier transmutation system. Uranium (~9 571 kg) separated from spent U-pins is manipulated as LLW or used for fresh U-pins preparation.

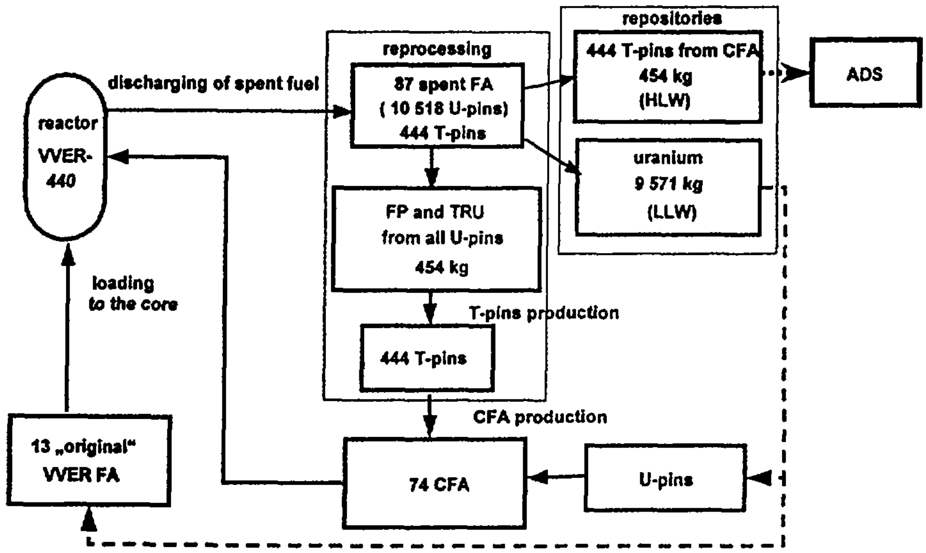

Fig.3 The partially closed fuel cycle

There is a large contrast of quantity of high level waste (HLW) released from current open fuel cycle (OFC) of VVER-440 reactor and from the model of partially closed fuel cycle (PCFC) - see material flows on Fig. 4 and Fig. 5.

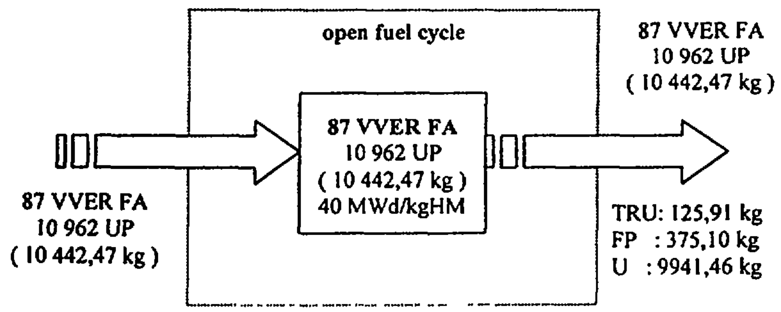

Fig 4 The material flow of OFC

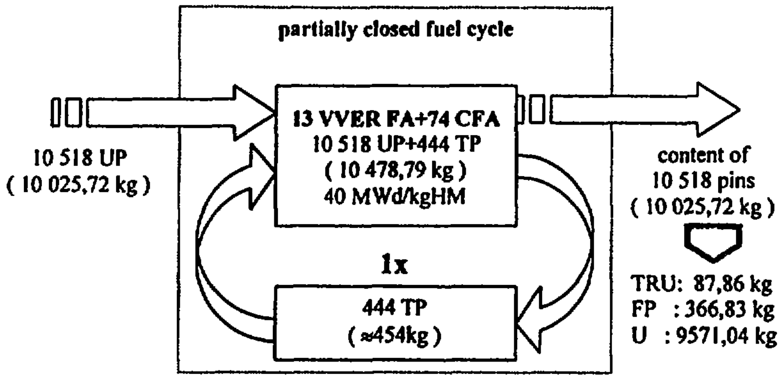

Fig.5 The material flow of PCFC

There is more than 10 t of HLW (TRU: 125.91 kg, FP: 375.10 kg, U: 9 941.46 kg) at OFC (Fig. 5) but less than 0.5 t of HLW (TRU: 87.86 kg, FP: 366.83 kg and no uranium) at PCFC (Fig. 6). Uranium is considered as LLW there. Other advantages of PCFC is saving of about 3.5 VVER FA's per fuel cycle as a consequence of reusing of TRU at 444 T-pins that were bred in U-pins at previous cycle.

Comparison of material flow at OFC and PCFC can be seen also in Table 1.

mass (kg)	open fuel cycle		partially closed fuel cycle	
	HLW repository	LLW repository	HLW repository	LLW repository
FP	375.1	0	366.83	0
TRU	125.91	0	87.86	0
U	9941.46	0	0	9571.04
TOTAL	10442.47	0	454.69	9571.04

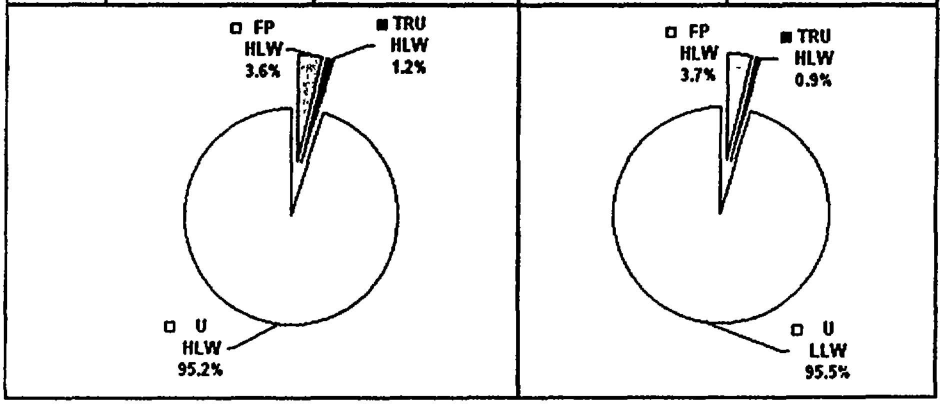

Table.1 Material flow comparison

7. CONCLUSION

Effective solution of fuel cycle back-end as a condition for nuclear energy success at energy sources competition was pointed out. Multi-tier transmutation system was outlined out as a progressive combination of revolutionary ADS and evolution of existing technology with impact on LWR's Reactor VVER-440 was suggested as first tier reactor at small nuclear economies based on VVER type reactors.

Introduction of transmutation process into the VVER-440 fuel cycle based on combined fuel assembly with transmutation pins was described. Resulting model of partially closed VVER-440 fuel cycle analysed by spectral code HELIOS exhibited significant advantages in comparison with common open fuel cycle. High level waste flow to the deep repository was reduced more than 20-times. Amount of resulting TRU was of 30 % smaller. Fresh fuel economy was reached by replacing of 444 fresh U-pins (equivalent of more than 3 fuel assemblies) by "fresh" T-pins.

Analytical result shows, that VVER-440 is reasonable candidate on first tier reactor at multi-tier transmutation system.

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