THE INTEGRATION OF FAST REACTOR TO THE FUEL CYCLE IN SLOVAKIA

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ABSTRACT

A very topical problem of nuclear power is the fuel cycle back-end. One of the options is a LWR spent fuel reprocessing and a fissile nuclides re-use in the fast reactor. A large amount of spent fuel has been stored in the power plant intermediate storage during the operation of VVER-440 reactors in Slovakia. This paper is based on an analysis of Pu and minor actinides content in actual VVER-440 spent fuel stored in Slovakia. The next part presents the possibilities of reprocessing and Pu re-use in fast reactor under Slovak conditions. The fuel cycle consisting of the VVER-440 reactor, PUREX reprocessing plant and a sodium fast reactor was designed. The last section compares two parts of this fuel cycle: one is UOX cycle in VVER-440 reactor and the other is cycle in the fast reactor - SUPER PHENIX loaded with MOX fuel (Pu + Minor Actinides). The starting point is a single recycling of Pu from VVER-440 in the FR. The next step is multirecycling of Pu in the FR to obtain equilibrium cycle. This article is dealing with the solution of power production and fuel cycle indicators. All kinds of calculations were performed by computer code HELIOS 1.10.

I. INTRODUCTION

The period of the nuclear power in the former Czechoslovakia started in august 1958 with the construction of small demonstration nuclear power plant called A1 which was a representant of a heavy water program in the former Czechoslovakia.[1] The conception of the NPP construction based on pressurised light water reactors was accepted after the closing of the heavy water project A1.[1] The NPP V1 construction with VVER-440 reactors began on 24th April 1972 in Jaslovske Bohunice.[1] The NPP V1 includes two VVER reactor units (type V230) with a unit electric power 440 MWe. Two reactors operated in NPP V1 were delivered from Russia. The electric power deficit in Slovakia caused the construction of NPP V2 as units 3 and 4. The NPP V2 uses the similar VVER reactors as V1 but there are big improvements in the systems of control and in nuclear safety standards (type V213).

The 1990's saw a V1 nuclear safety improvement process in Jaslovske Bohunice under the Small-Scale and Gradual Reconstruction programmes.[1] The NPP V1 units 1 and 2 were operated since 1978 to 2008. The unit 1 was stopped on 31st December 2006 and unit 2 on 31st December 2008.
The reactor units 3 and 4 have been regular operated since 1984 and 1985. Four reactor units have produced a large amount of spent fuel during a thirty-year operation. The spent fuel has been stored in the NPP intermediate storage and the question of the final spent fuel treatment becomes pressing.[2] Some countries see the solution of the spent fuel treatment in an underground disposal but spent fuel stored for 300 or 1000 years is not a guarantee of safety in the case of long-lived nuclides. One of the options is a transmutation process which changes long-lived heavy nuclides into nuclides with the markedly shorter time of decay or into stable nuclides. The condition of transmutation is an increased neutron flux during the fuel burn up. This condition is completely fulfilled in fast reactors. The French fast reactor SUPER PHENIX was chosen for analysis of heavy nuclides (Pu + Minor Actinides) burning transmutation. The complex model of SUPER PHENIX in a spectral code HELIOS 1.10 consists of the fuel and fertile assemblies. The SUPER PHENIX results were compared with the results of the operated VVER-440 spent fuel (4.25 % U-235 + 3.35 % Gd_2O_3). HELIOS 1.10 was used for modelling of the VVER-440 assembly in an infinite lattice.[2]

II. INVENTORY FROM NPP V1 JASLOVSKE BOHUNICE

The reactor unit 1 of the NPP V1 was operated for 27 core cycles (1978 - 2006) and the unit 2 was in operation for 28 core cycles (1979 - 2008). The spent fuel was transported to the Soviet Union during the first operated years and later on it was stored in the NPP intermediate storage. This paper shows the overview of the reactor units 1&2 inventory.[3] At the beginning of the operation both reactor units used old types of fuel assemblies with the uniform enrichment 1.6 %, 2.4 % and 3.6 % of U-235. The nonuniform fuel assemblies (radial profilation of enrichment) with average enrichment 3.82 % of U-235 were loaded only during several operated cycles before NPP V1 shutdown. The number of the VVER-440 fuel assemblies stored in the intermediate storage in Jaslovske Bohunice is listed in Table I.

TABLE I
The Number of the VVER-440 Spent Fuel Assemblies from NPP V1[3]

Reactor unit / Fuel type	Unit 1 (V1)	Unit 2 (V1)	Unit1 + Unit 2 (V1)
1.6 % U-235	24	18	42
2.4 % U-235	491	356	847
3.6 % U-235	1788	1824	3612
3.82 % U-235	216	426	642
Total	2519	2624	**5143**

The overview of U, Pu, Am, Cm, actinides and fission products masses is listed in Table II. The listed weight values are calculated to the date 31st December 2056.

TABLE II

The Included Element Masses in the Spent Fuel from NPP V1[3]

Nuclide	Mass [kg]	
U-233	6.18436E-03	Sum of uranium 5.62261E+03
U-234	3.87601E+01	
U-235	6.30601E+03	
U-236	2.55410E+03	
U-238	5.81648E+05	
Np-237	3.33015E+02	
Pu-238	6.34434E+01	Sum of plutonium 5.62261E+03
Pu-239	3.81916E+03	
Pu-240	1.40343E+03	
Pu-241	4.93069E+01	
Pu-242	2.87271E+02	
Pu-244	1.58723E-08	
Am-241	7.89224E+02	Sum of americium 8.51769E+02
Am-242m	4.81460E-01	
Am-243	6.20634E+01	
Cm-242	1.25665E-03	Sum of curium 2.78415E+00
Cm-243	5.29711E-02	
Cm-244	1.95307E+00	
Cm-245	6.93264E-01	
Cm-246	8.34365E-02	
Cm-248	1.49047E-04	
Cf-252	1.02119E-13	
H-3	1.08231E-03	Sum of FP 1.54463E+03
Be-10	7.94626E-05	
C-14	1.59489E-05	
Se-79	2.97670E+00	
Kr-85	3.05702E-01	
Sr-90	7.54614E+01	
Zr-93	2.88017E+02	
Nb-93m	2.81714E-03	
Nb-94	2.85758E-04	
Tc-99	4.78265E+02	
Ru-106	2.73846E-14	
Pd-107	1.32205E+02	
Ag-108m	7.69101E-05	
Cd-109	3.49956E-20	
Sn-121m	1.20585E-02	
Sb-125	3.61328E-06	
Sn-126	1.15631E+01	
I-129	1.09859E+02	
Ba-133	1.31485E-09	
Cs-134	8.21783E-07	
Cs-135	2.51356E+02	
Cs-137	1.87658E+02	
Ce-144	1.84748E-18	
Pm-147	5.21090E-05	
Sm-151	6.80640E+00	
Eu-152	1.42736E-03	
Eu-154	1.37908E-01	
Actinides	5.97357E+05	
FP	1.54463E+03	
Total	5.98902E+05	

The major part of the total mass consists of U-238. U-238 makes more than 95 % of the total spent fuel amount. The weight of fissionable nuclides (U-235 + Pu-239 + Pu-241) is 1.0174E+04 kg.[3] SCALE 4.4 system was used for the determination of nuclide composition for the each operated and spent VVER-440 assembly.[3] The average burn up of assembly and cycle parameters were calculated by the Russian code BIPR 7.[4]

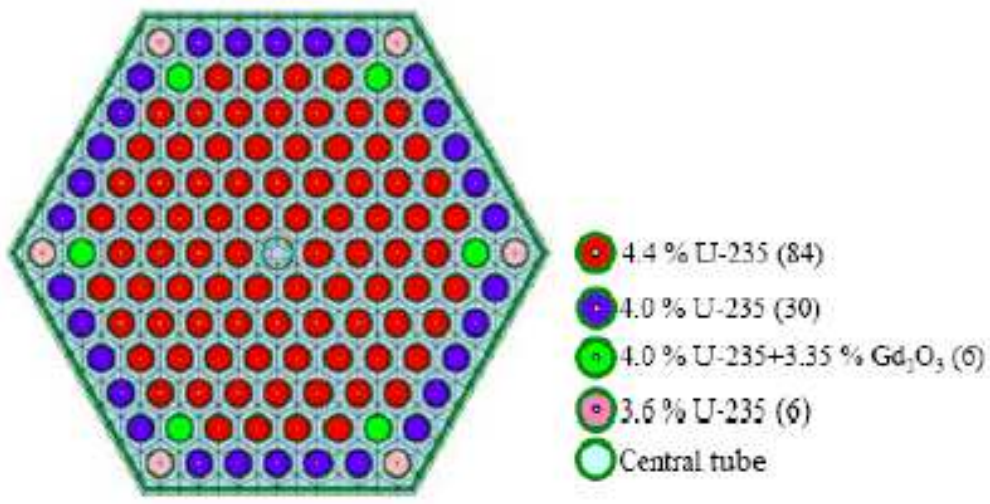

Fig. 1. The VVER-440 fuel assembly (4.25 % U-235 + 3.35 % Gd_2O_3

III. VVER-440 & SUPER PHENIX

The VVER-440 core consists of 349 hexagonal fuel assemblies. At present the VVER-440 fuel assembly with enrichment 4.25 % of U-235 and 3.35 % of Gd_2O_3 is the most advanced assembly used in Slovak nuclear reactors. This type of assembly was modelled in an infinite lattice (fig. 1) and computer code HELIOS 1.10 was used.

The differences between core parameters of SUPER PHENIX and VVER-440 are listed in Table III.

The central part of the SUPER PHENIX core consists of fuel subassemblies which include a fuel part surrounded by a fertile part.[5] This configuration is that of a homogeneous reactor, in other words the one in which the fuel and blanket parts are distinctly separate: the fuel part in the centre, the blanket part surrounding the fuel. This is the configuration which was adopted for all the FRs in operation up to now.[5]

TABLE III
The comparison of parameters between SUPER PHENIX[5] and VVER-440

Parameter / Type of reactor	SUPER PHENIX	VVER-440
Electric power [MWe]	1450	440
Efficiency [%]	40	30
Fuel	$(U, Pu)O_2$	UO_2 + 3.35 % Gd_2O_3
Final burn up (fuel) [MWd/kgU]	136 000	50 000
Final burn up (fertile) [MWd/kgU]	4 000	---
Initial enrichment of Pu [%]	23.2	0.0
Initial enrichment of U-235 [%]	0.25	4.25
Initial enrichment of MA [%]	2.7	0.0
Amount of fuel [tHM]	(37.1 + 76.5) 113.6	44.1
Number of fuel assemblies	364	349
Number of fertile assemblies	233	0
Number of pins per fuel assembly	271	126
Number of pins per fertile assembly	91	0
Coolant temperature [°C]	550	280
Coolant composition	Na	H_2O

The reason is the application of PSEUDO assemblies (fig. 3 and 4) in the HELIOS model described in following paragraph.

IV. MODEL OF SUPER PHENIX IN HELIOS 1.10

The first modelling plan was to simulate 1/6 core (fig. 2) of SUPER PHENIX but during the model construction some software limits were imposed by HELIOS.[2] The main limit is the operation memory allocation. Small length of memory causes the using of pseudo assemblies (fig. 4 and 5). The pseudo assembly consists of 91 fuel pins. The number is approximately three times less than the real number of pins included in the fuel assembly (Table III). On the fig. 3 is situated the real cross section of SUPER PHENIX fuel assembly. Another software limit caused reduction not only at the assembly level but also at the degree of the core. HELIOS is able to run the job with 26 pseudo assemblies which is the coloured part on fig. 2. Higher reductions of fuel assembly details for getting full 1/6 core of SUPER PHENIX could lead to degraded final results. For that reason a colour part of the fig. 2 was chosen. The fertile assembly has the same pin number as the fuel pseudo assembly but in the centre a hole is missing.[2]

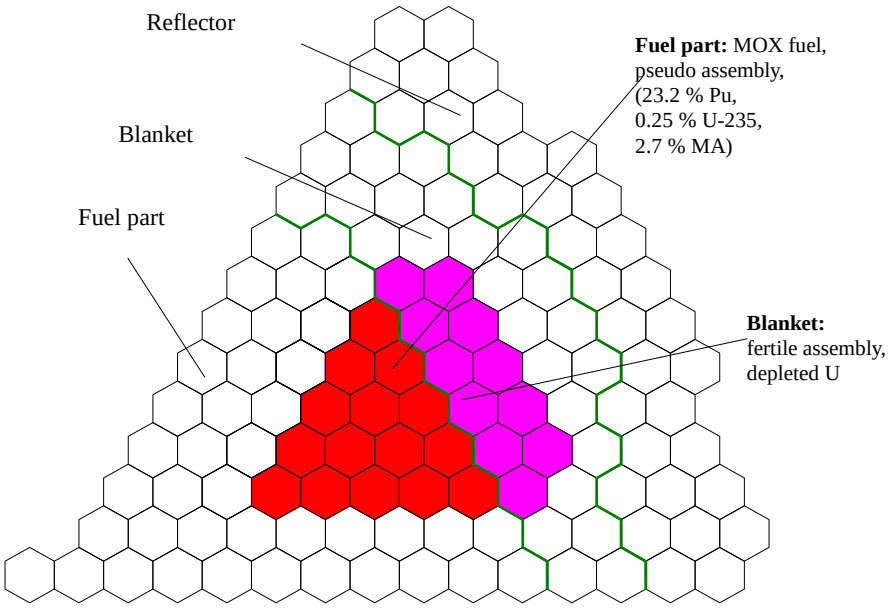

Fig. 2. 1/6 core of SUPER PHENIX, colour part: subject of calculation[2]

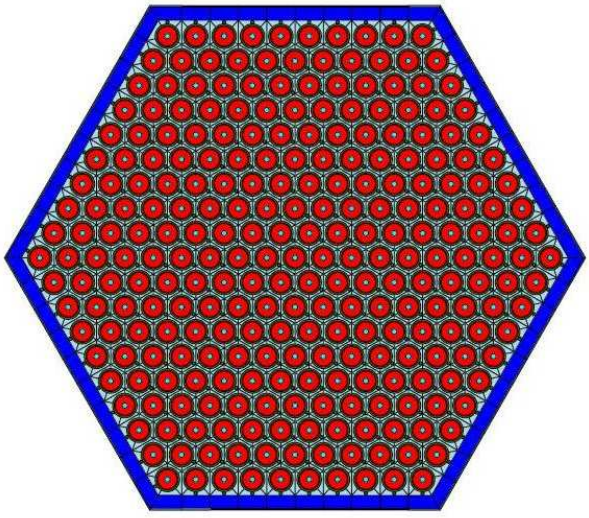

Fig. 3. Real fuel assembly of SUPER PHENIX[5]

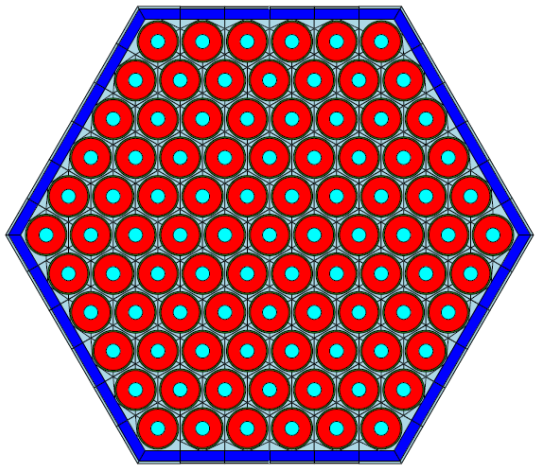

Fig. 4. Fuel pseudo assembly of SUPER PHENIX[2]

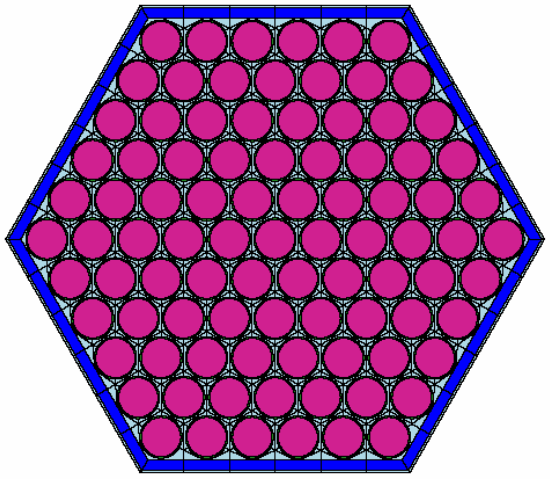

Fig. 5. Fertile assembly of SUPER PHENIX[2]

V. MULTIRECYCLING OF PU AND MA IN SUPER PHENIX

The FR cycle start is a single recycling of VVER-440 Pu. The first fuel loading for the SUPER PHENIX core creates the re-use Pu separated from the NPP V1 spent fuel. The all Pu comes from the old types of fuel assemblies could be burnt by the way showed on fig. 6.[6] The next step is the Pu recycling from the new types of VVER-440 fuel assemblies (4.25 % U-235 + 3.35 % Gd_2O_3). Plutonium is recycled in U - Pu oxide fuel. The aqueous partitioning system is used and no separated Pu storage exists in this fuel cycle. The FP are disposed directly to the storage. Reprocessing of irradiated FR MOX fuel after 5 years of cooling produces the Pu. Pu is recycled in the same FR cycle,

in a MOX fuel with a 136 GWd/tU burn up. A two-year interval for reprocessing, MOX fabrication and loading to the reactor is taken into account. The spent MOX fuel as well as the high level waste after reprocessing is cooled for 45 years before sending them to the final repository. The reprocessing loss rate is 0.1 % for Pu and MA.[6]

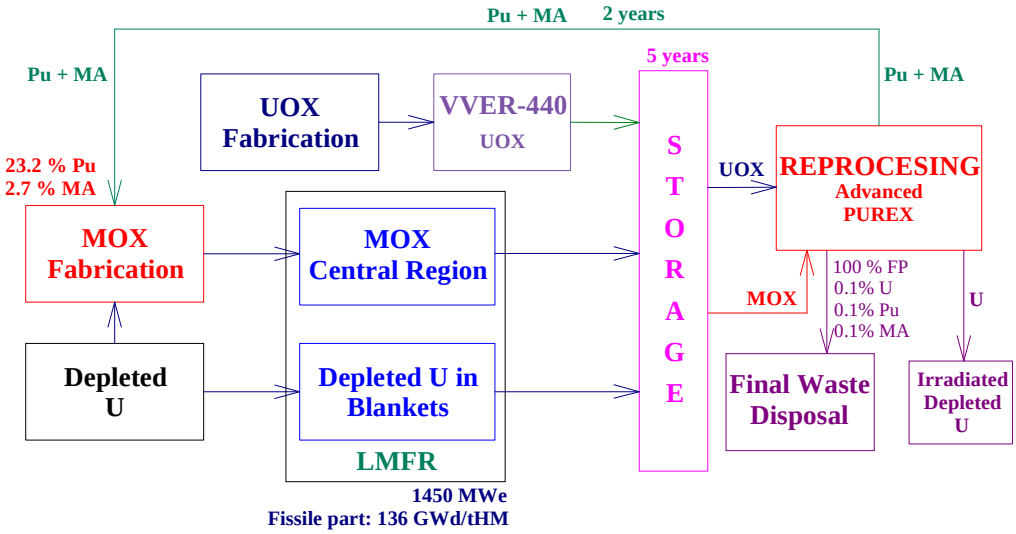

Fig. 6. Multirecycling of Pu and MA in FR[6]

VI. RESULTS

The result evaluation of this study is concentrated on the weight concentration (actinides and FP) in the SUPER PHENIX and VVER-440 spent fuel. The close attention is dedicated to the fuel cycle and final repository indicators.

The chosen actinides and FP of VVER-440 spent fuel are listed in Table IV. These values are used as exposed results for the confrontation of two different reactor kinds.

The content of Pu in spent MOX fuel of SUPER PHENIX during infinite recycling is shown on fig. 7. Concentrations of Pu isotopes are very stable during all cycles. The amount of Pu-239 in fuel part is slightly lower than 10 % in equilibrium cycle (Table V) and in fertile part a little bit less than 1.6 % (Table VI). The concentration of Pu in fuel part reaches app. 19 % in equilibrium cycle. Mass concentration of Pu in the fertile part is higher than 1.6 %. Pu in the fertile part includes 97.2 % of Pu-239. Pu-239 curve of fuel part on fig. 7 starts from the value 1.11E+05 g/tHM and slowly goes down from cycle to cycle. This effect is caused by the influence of reprocessed VVER-440 spent fuel.

TABLE IV
Weight concentration of nuclides in VVER-440 spent fuel

VVER-440		
Cycle/Nuclides	Initial [g/tHM]	1st cycle [g/tHM]
U-235	4.2527E+04	8.2770E+03
Pu-238	---	2.8394E+02
Pu-239	---	6.0891E+03
Pu-240	---	2.7393E+03
Pu-241	---	1.7061E+03
Pu-242	---	7.6705E+02
Am-241	---	6.5113E+01
Pu-Total	---	**1.2207E+04**
MA-Total	---	**1.0768E+03**
Sr-90	---	7.7520E+02
Tc-99	---	1.1322E+03
I-129	---	2.2953E+02
I-131	---	7.4091E+00
Cs-137	---	1.7878E+03
Sm-149	---	2.6489E+00
Total FP	---	**4.5688E+04**

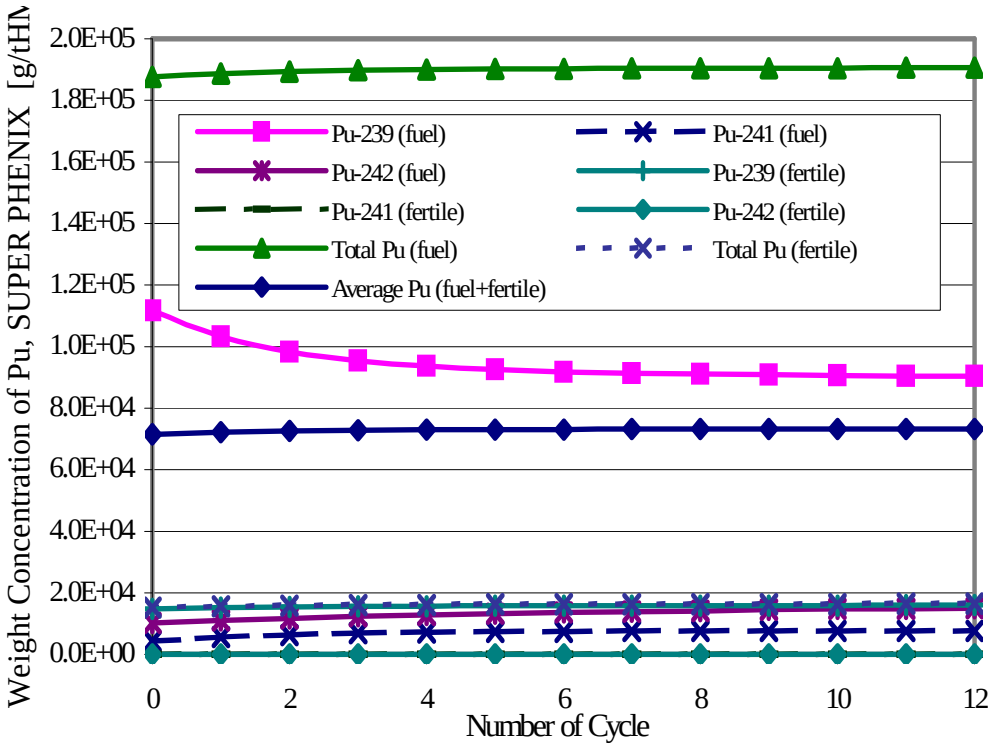

Fig. 7 Development of Pu production in SUPER PHENIX

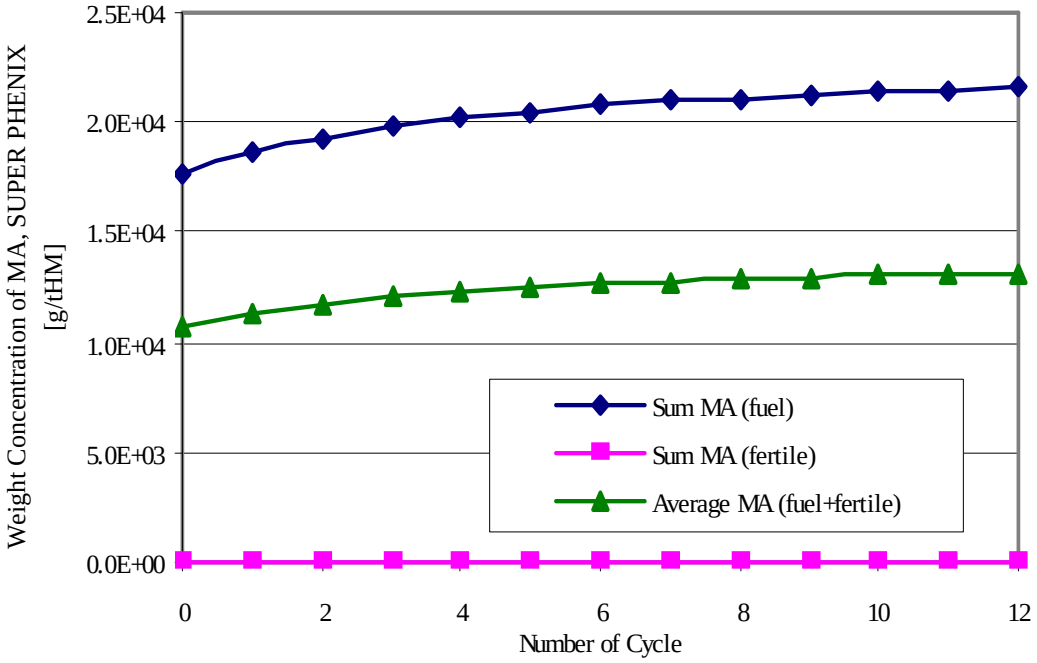

Fig. 8 Accumulation of MA in the fuel and fertile part of the SUPER PHENIX core

TABLE V

Weight concentration of nuclides in SUPER PHENIX spent fuel (fuel part) after 5 years of cooling

SUPER PHENIX, fuel part			
Cycle/ Nuclides	Initial 1st cycle [g/tHM]	1st cycle [g/tHM]	Equilibrium [g/tHM]
U-235	2.5000E+03	1.1184E+03	1.0260E+03
Pu-238	2.9780E+03	6.7227E+03	6.0773E+03
Pu-239	1.5758E+05	1.1178E+05	9.0360E+04
Pu-240	5.7908E+04	5.4511E+04	7.1409E+04
Pu-241	2.0345E+03	4.3841E+03	7.7153E+03
Pu-242	1.1853E+04	1.0282E+04	1.5001E+04
Am-241	1.7943E+04	1.0139E+04	7.3708E+03
Pu-Total	**2.3236E+05**	**1.8768E+05**	**1.9056E+05**
MA-Total	**2.7000E+04**	**1.7643E+04**	**2.1563E+04**
Sr-90	---	9.9511E+02	9.6660E+02
Tc-99	---	3.1879E+03	3.1047E+03
I-129	---	9.3459E+02	9.0033E+02
I-131	---	1.6595E-13	1.6594E-13
Cs-137	---	4.3993E+03	4.3847E+03
Sm-149	---	8.4482E+02	8.3538E+02
Total FP	---	**1.2145E+05**	**1.2134E+05**

TABLE VI

Weight concentration of nuclides in SUPER PHENIX spent fuel (fertile part) after 5 years of cooling

SUPER PHENIX, fertile part			
Cycle/ Nuclides	Initial 1st cycle [g/tHM]	1st cycle [g/tHM]	Equilibrium [g/tHM]
U-235	2.5000E+03	2.1479E+03	2.1205E+03
Pu-238	---	3.6151E+00	3.9131E+00
Pu-239	---	1.4842E+04	1.5984E+04
Pu-240	---	3.7250E+02	4.4670E+02
Pu-241	---	5.4357E+00	7.2023E+00
Pu-242	---	8.6289E-02	1.2725E-01
Am-241	---	1.6406E+00	2.1829E+00
Pu-Total	---	**1.5224E+04**	**1.6442E+04**
MA-Total	---	**4.9834E+01**	**5.0645E+01**
Sr-90	---	3.1197E+01	3.2833E+01
Tc-99	---	7.8513E+01	8.3540E+01
I-129	---	2.0780E+01	2.2164E+01
I-131	---	2.4606E-13	2.4606E-13
Cs-137	---	9.7572E+01	1.0434E+02
Sm-149	---	2.4989E+01	2.6136E+01
Total FP	---	**2.7742E+03**	**2.9569E+03**

The last figure (fig. 8) includes the accumulation of MA in SUPER PHENIX. The MA value moves up depending on cycle number. During the infinite recycling of MA the sums of MA are still lower than the initial (2.7 %) content.

TABLE VII

Average weight concentration of nuclides in SUPER PHENIX spent fuel (fuel + fertile part) after 5 years of cooling

SUPER PHENIX, fuel + fertile part			
Cycle/ Nuclides	Initial 1st cycle [g/tHM]	1st cycle [g/tHM]	Equilibrium [g/tHM]
U-235	2.5000E+03	1.8117E+03	1.7631E+03
Pu-239	5.1463E+04	4.6500E+04	4.0274E+04
Pu-241	6.6444E+02	1.4354E+03	2.5245E+03
Pu-Total	**7.5883E+04**	**7.1546E+04**	**7.3307E+04**
MA-Total	**8.8178E+03**	**5.7955E+03**	**7.0762E+03**
Total FP	---	**4.1532E+04**	**4.1619E+04**

TABLE VIII

Fuel cycle indicators

Type of reactor	VVER-440, UOX	SUPER PHENIX, MOX	
		Fuel part	Fertile part
Indicator/Cycle	1st cycle	Equilibrium	Equilibrium
1. Pu and MA transmutation rate (Output - Input)			
Pu [g/TWhe]	---	3.1738E+04	---
MA [g/TWhe]	---	4.1644E+03	---
2. Mass of fuel entering reactor			
Fuel [g/TWhe]	2.2727E+06	7.6593E+05	2.6780E+07
3.Rate of Pu and MA in the fuel entering reactor			
Pu [%]	---	2.3236E+01	---
MA [%]	---	2.7000E+00	---
4. Rate of Pu and MA in the spent fuel (5 years of cooling)			
Pu [%]	1.2207E+00	1.9056E+01	1.6442E+00
MA [%]	1.0768E-01	2.1563E+00	5.0645E-03
5. Mass of reprocessed fuel			
Fuel [g/TWhe]	2.2727E+06	7.6593E+05	2.6780E+07
6. Mass of fuel to the repository			
Sum of repr. losses [g/TWhe]	2.2280E+03	6.5906E+02	7.6341E+02
Sum of FP [g/TWhe]	1.0743E+05	9.2940E+04	2.2648E+03
Total loss. + FP [g/TWhe]	1.0966E+05	9.3599E+04	3.0282E+03
Irradiated U [g/TWhe]	2.1960E+06	4.9609E+05	7.5003E+05
7. Energy recovery per t of natural U			
Fission actinides [g/TWhe]	3.7993E+04	7.5905E+04	1.3872E+04
Equivalent weight [tU]	3.4788E+00	2.1450E+01	3.9202E+00
Recovery energy [TWhe/tU]	4.1902E-01	3.6223E-01	7.0468E-01
8. Average quantity of Pu separated in fuel cycle			
Pu [g/TWhe]	1.1574E+04	1.9037E+05	1.6425E+04
9. Average content of Pu-239 and Pu-241 in Pu in the moment of separation			
Pu-239 [%]	5.2558E+01	4.7417E+01	9.7215E+01
Pu-241 [%]	1.4726E+01	4.0487E+00	4.3805E-02
10. Average content of Pu-239 and Pu-241 in Pu after separation			
Pu-239 [%]	5.2505E+01	4.7370E+01	9.7118E+01
Pu-241 [%]	1.4711E+01	4.0446E+00	4.3761E-02
11. Amount of finally disposed Pu			
Pu [g/TWhe]	2.7243E+01	1.4596E+02	1.2593E+01
12. Inventory of the enriched U in front end			
U-235 in fresh fuel [g/TWhe]	9.9937E+04	1.9148E+03	1.9148E+03
U-235 in spent fuel [g/TWhe]	1.9463E+04	7.8585E+02	1.6241E+03
13. Mass of separated U			
Separated U [g/TWhe]	2.1623E+06	4.9558E+05	7.4905E+05

Table VIII includes 13 fuel cycle indicators of VVER-440 and SUPER PHENIX fuel cycle. The values of cycle indicators between VVER-440 and SUPER PHENIX are seemingly very different but it is necessary to expect the big difference between electric energy production of SUPER PHENIX and VVER-440. The SUPER PHENIX is able to produce 3.295 more electric power than VVER-440.

VII. CONCLUSION

With the best will the probability of FR real application for the electricity production in Slovakia condition is low. This study only indicates the useful utilization of the fissionable nuclides included in the spent fuel. Support of FR technology holders should be taken into account.

ACKNOWLEDGMENTS

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NOMENCLATURE

FP	- Fission Products	FR	- Fast Reactor
MA	- Minor Actinides	MOX	- Mixed Oxide Fuel
NPP	- Nuclear Power Plant	UOX	- Uranium Oxide Fuel

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