

SECTION 2

THERMAL AND FAST REACTOR MATERIALS

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ON THE OPTIONS OF UKRAINE'S NUCLEAR FUEL CYCLE

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The current Energy Strategy of Ukraine establishes that electricity production at NPPs in future retains at least approximately equivalent to that currently produced. How this could be accomplished is hidden in general statements, which also applies to the issues and challenges of the Nuclear Fuel Cycle. It is known that NFC is the key indicator that determines the economy of NE. The uncertainty about which NFC options need to be developed and which NFC stages and steps need to be implemented in the time perspective complicate making timely decisions. This paper presents a summary of the cost options for an open and closed NFC with WWER and CANDU reactors using the costs of stages currently accepted in the world.

INTRODUCTION

Nuclear Fuel Cycle is fundamental for the functioning of Nuclear Energy. The use of potentially hazardous nuclear materials in power generation brings forth the demand for ensuring public safety during all

NFC steps and stages that is fulfilled by the reliable isolation or disposal of all radioactive products formed throughout the whole way of nuclear fuel management, which is reflected in the diagram of full (complete) NFC presented in Fig. 1.

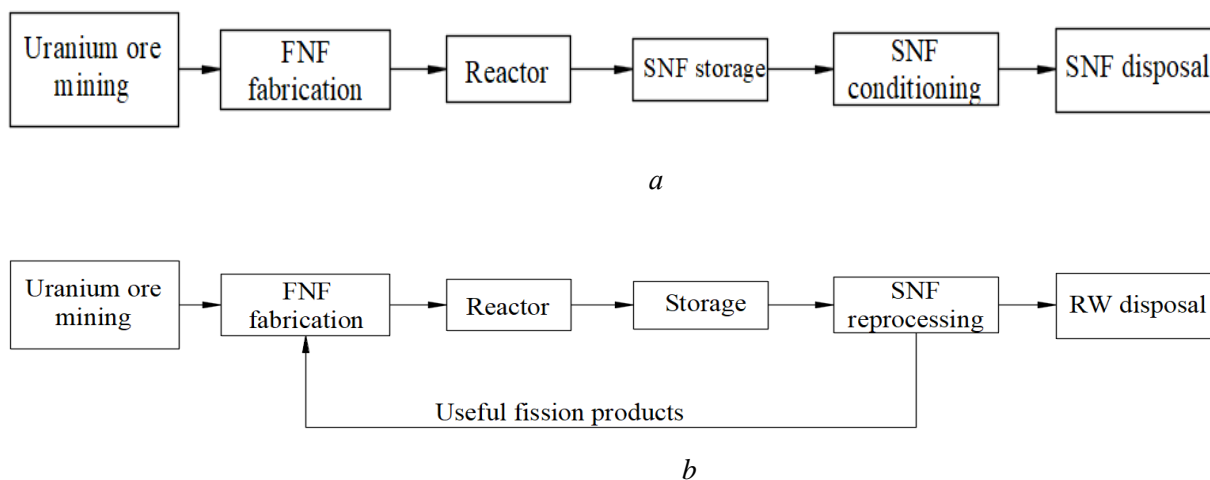


Fig. 1. Diagram of full (complete) NFC: a – open NFC, b – closed NFC

Due to the fact, that technological operations have not been amply elaborated on a commercial scale and because of the economic factors, currently, at some SNF management stages in much of the world, the so-called delayed decision prevails. It means that SNF is safely stored until a decision is made on what should be done with it: recycling and using useful products in subsequent NFCs, or conditioning and disposal in geological formations. Sweden and Finland chose the latter option.

Today, when we speak about the Nuclear Fuel Cycle in Ukraine, we mostly refer to the concept of delayed decision on recycling WWER SNF and the need to address the issues related to NFC closure.

Fig. 2 presents a diagram of the Ukrainian WWER-1000 NFC developed based on the decisions adopted. Attention should be paid to one of the main stages of Ukraine's nuclear fuel cycle – SNF reprocessing. In accordance with the adopted decisions, part of SNF will be reprocessed in the Russian Federation (RF) and the products of reprocessing – radioactive waste (RW), uranium and plutonium will be returned to Ukraine. The services for all operations including SNF storage have already been paid. The other part of SNF will be stored in Ukraine until a decision on what to do with it is made, which implies costs at all SNF management stages that will have to be implemented.

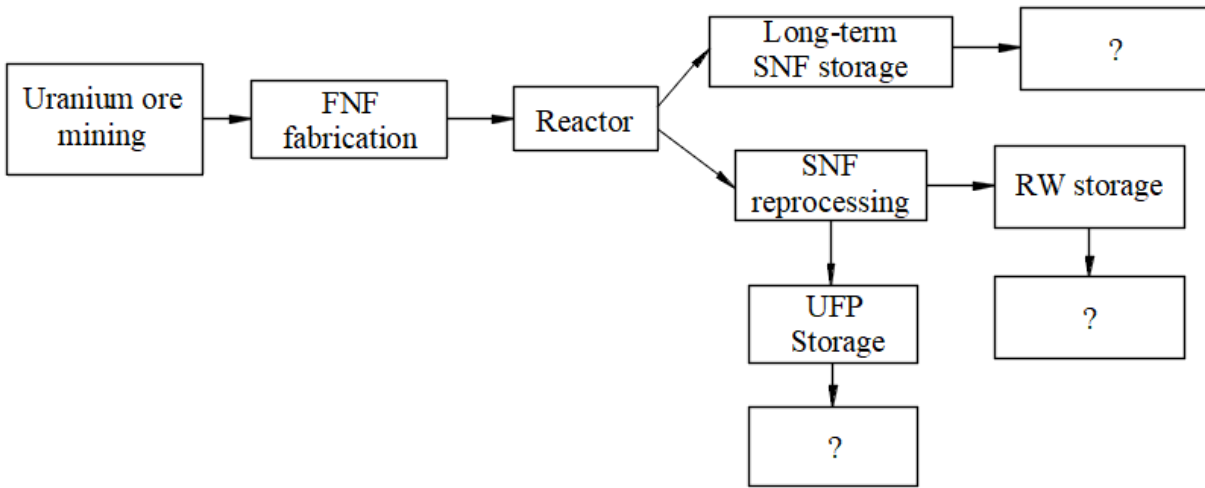


Fig. 2. Ukraine's NFC with WWER-1000 reactors

Today, it is impossible even to predict when and who will make a final decision on the of high-level waste (HLW) (including SNF) management. It means that SNF will be stored in Ukraine indefinitely. It is quite possible that the announced 100-year period of SNF storage in the centralized storage facility can be significantly exceeded. Long-term storage of SNF results in significant changes in the isotopic inventory of material, including decreasing the amount of fissile isotopes, which leads to increasing the costs of SNF management. Expectation that introduction of fast reactors (FR) will allow burning of unwanted (long-lived) isotopes does not solve the problem as a whole. To date, the considered options of FRs basically substantiate possibility of implementation of the equilibrium cycle: burning of isotopes, accumulated during the previous cycle. For burning of large quantities of long-lived isotopes, it will be necessary to develop special-purpose (systems) reactors and substantiate their economic feasibility.

Special hopes are placed on hybrid thermonuclear installations that are being considered at the level of fundamental research. Due to large number of physical, materials science and technological issues, it is impossible to predict the time of practical implementation of this idea. It is known that the dates of

implementation of the demonstration thermonuclear facilities have been permanently postponed.

The use of CANDU reactors in the structure of nuclear power (NP) is primarily aimed at effective use of nuclear fuel. The proposed two types of reactors operating on natural or slightly enriched uranium practically imply existence of an open NFC (Fig. 1,a). The use of heavy water as a neutron moderator ensures deep burning of ^{235}U and ^{239}Pu produced, and makes further reprocessing of SNF impractical. The possibility of using natural enrichment uranium and simple fuel rod design are most attractive in the economy of NFC with CANDU reactors, and these factors arise increased interest in terms of organization of domestic production of fresh nuclear fuel when addressing the tasks of introduction of CANDU reactors in the structure of the Ukrainian NP. CANDU reactors operating on natural uranium have a negative feature known as positive reactivity coefficient at coolant loss. In Ukraine, reactors having a positive reactivity coefficient are prohibited. Using low-enriched uranium ($\approx 1.2\% \text{ }^{235}\text{U}$) as fuel allows eliminating this factor and ensures a negative reactivity coefficient. In this case, CANDU NFC economy is proposed to be considered in a tandem cycle: WWER – CANDU reactors (Fig. 3).

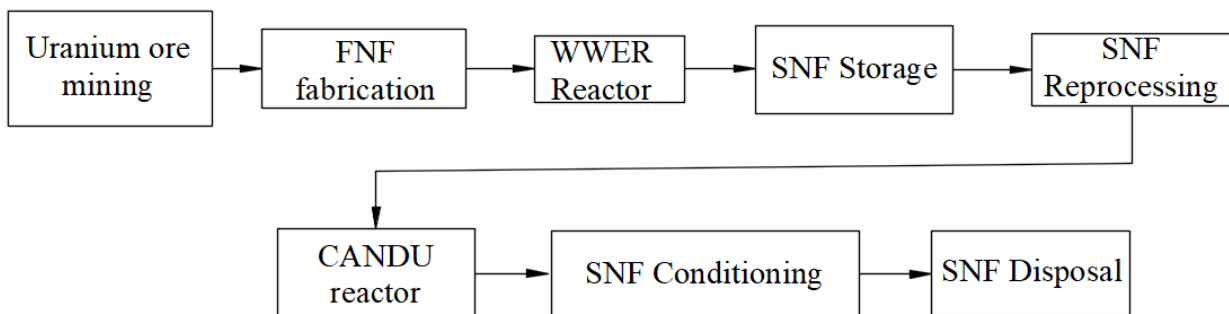


Fig. 3. NFC, tandem cycle WWER-CANDU

The purpose of this paper was to consider the most economically viable Nuclear Fuel Cycles with WWER reactors based on the NFC options currently implemented in the world and that are realizable in Ukraine. They are as follows:

1. Open NFC.
2. Closed NFC with WWER-1000 reactors.

Options:

2.1. Recycled uranium is subject to enrichment by known methods, such as, gas-centrifuge enrichment. Plutonium is stored for further use (ReU);

2.2. Recycled uranium is re-enriched in U²³⁵ from an internal source; plutonium is stored for further utilization (ReU+²³⁵U);

2.3. Recycled uranium and plutonium are used for fabrication of MOX fuel.

3. NFC with introduction of CANDU reactors in the structure of Ukraine's NP.

MATERIALS AND METHODS

This paper does not address NFCs with fast reactors in the structure of Ukrainian nuclear energy. This issue should be considered separately, and its solution largely depends on whom Ukraine will cooperate with on all problems of nuclear energy.

For the economic assessments of all NFC steps and operations performed in relation to Ukraine, the values used in the world are accepted (Tabl. 1), in order to compare different options in a single approach. It should be noted that for many operations, only laboratory studies and economic indicators based on them are available. Large-scale commercial implementation of the technologies can significantly change the economic indicators.

Table 1

Economic characteristics of NFC stages for WWER reactors [1–9]⁴

No	Costs of NFC Stages	Value used in the study
1	Natural uranium cost \$/kg HM ¹	100
2	Conversion, \$/kg HM	10
3	Enrichment ² , \$/kg SWU	115
4	Fabrication of fuel from natural uranium, WWER, \$/kg HM	275
5	Fabrication of MOX fuel, WWER, \$/kg HM	1200
6	Fabrication of fuel from natural uranium, CANDU, \$/ kg HM	65
7	FA transportation ³ , \$/kg HM	5
8	SNF transportation ⁴ , \$/kg HM	69
9	SNF long-term storage, \$/kg HM	230
10	SNF reprocessing, \$/kg HM	800
11	SNF conditioning, \$/kg HM	510
12	SNF disposal, \$/ kg HM	100

¹ HM – heavy metal.

² ²³⁵U content in reject materials was taken to be 0.3%.

³ FA — fuel assemblies.

⁴ Calculation assumed that the costs of conversion, enrichment and fabrication of fuel from recycled uranium is 10% higher than the costs of these stages for fresh nuclear fuel (FNF) of natural uranium.

Table 2
Economic characteristics of NFC stages for CANDU reactors [7–9]⁴

No	Costs of NFC Stages	Value used in the study
1	Natural uranium cost \$/kg HM	100
2	Conversion, \$/kg HM	10
3	Enrichment ² , \$/kg SWU	115
4	Fabrication of fuel from natural uranium, WWER, \$/kg HM	65
5	Fabrication of MOX fuel, WWER, \$/kg HM	558
6	FA transportation ³ , \$/kg HM	5
7	SNF transportation ⁴ , \$/kg HM	5
8	SNF long-term storage, \$/kg HM	47
9	SNF conditioning, \$/kg HM	202
10	SNF disposal, \$/ kg HM	90

Let us consider the NFC options.

OPEN NFC

Open NFC (see Fig. 1,a) is characterized in that at the stage of SNF management it is necessary to address complicated tasks during two main steps. The first task is to develop a technology for SNF conditioning. The second task is to choose and substantiate geological formations for SNF disposal. Works that must be done within the frame of these tasks are complex and long-term. Specialized organizations are needed for performance of all research, design and technology work. Of course, such works could best be accomplished in cooperation with leading foreign partners and with the use of all accumulated international experience.

It is virtually impossible to expect that you can buy a complete package of design and technological solutions for SNF conditioning. Developers, such as Sweden, conduct such works for specific designs and characteristics of SNF in the form of fuel assemblies (FA). Even if you buy the main technological solutions, you will have to upgrade the technology to comply with the specifics of WWER FA characteristics. For Ukraine, the need to solve the problems at the stage of SNF management is inevitable. It must be borne in mind that in Ukraine, in addition to SNF from WWER reactors, RBMK SNF is stored that is economically unfeasible to reprocess, and this means that it must be conditioned and disposed of in geological formations.

The tasks of searching and substantiation of geological formations for disposal of high level radioactive waste must be completed at a faster pace, as vitrified HLW from reprocessed WWER SNF will start to arrive in in Ukraine in the coming years, and the problem of their safe management cannot be solved by establishing temporary storage facilities.

The economic estimates show that for an open WWER-1000 NFC with a 4-year fuel operation cycle, at the current level of prices for uranium and fresh nuclear fuel fabrication (Table 1), the fuel component of the cost of electricity amounts to $7.84 \cdot 10^{-3}$ \$(/kWh) (Table 3).

Table 3
Fuel component of the cost of electricity for an open NFC, 10^{-3} \$(/kWh)

Stages, steps	Costs
FNF fabrication from natural uranium	5.46
FNF transportation	0.01
SNF transportation	0.18
SNF storage	0.6
SNF conditioning	1.33
SNF disposal	0.26
Total	7.84

USE OF RECYCLED URANIUM IN WWER REACTORS

It is estimated that by 2050, Ukrainian WWER-440 and WWER-1000 reactors operated at the current power level, will produce 14906 t HM of SNF, which can be used for fabrication of 13100 t of recycled uranium and 114 t of plutonium (at an average 1% content of ^{235}U and 0.8% of plutonium in the SNF), including 2800 t of recycled uranium and 24.8 t of plutonium separated from the SNF during reprocessing in the Russian Federation [10-12], and 10300 t of recycled uranium and 89.2 t of plutonium from the SNF that is stored in Ukraine and will be reprocessed abroad in future.

Since SNF reprocessing in the Russian Federation has already been paid, the recycled uranium and plutonium have a zero cost and logically, they could be used for manufacturing WWER-1000 fuel. The cost of these products, in the equivalent of the natural uranium cost, is estimated at \$1 050 million. At first glance, it seems that this value is the economic effect of the use of useful fission products (UFP), however due to its characteristics, the economic effect from the use of UFP depends on the implemented NFC options. The differences are determined by the final composition of fabricated fresh fuel and the cost of manufacturing steps. Besides, it is difficult to determine the cost of fresh nuclear fuel as it depends on who will own the UFP. Therefore, in our estimates, we take into account only possible actual costs of UFP management.

It is known that during SNF reprocessing, when ^{238}U and ^{235}U are extracted, the ^{232}U and ^{236}U content in recycled uranium increases as compared to natural uranium, which increases radioactivity of the material and impairs efficiency of its utilization. Increasing the number of recycles decreases NFC performance [13, 14].

Additional consumption of natural uranium, due to the need to compensate for the presence of ^{236}U and to reduce the amount of ^{232}U , degrades the efficiency of reusing reprocessed uranium. Therefore, this study considers economic indicators of the NFC for only a single-cycle application of recycled uranium. The tasks

of using recycled uranium can only be considered in relation to the cost of natural uranium. For future introduction of the nuclear fuel cycle using recycled uranium for fabrication of fresh nuclear fuel, a detailed analysis is required of all issues related to the economy of multiple use of recycled uranium, for example, in the REMIX cycle.

Implementation of the tasks on the use of recycled uranium begins with development of requirements for the material separated during SNF reprocessing.

As a rule, large companies establish a single chain: SNF reprocessing, operations with recycled uranium and plutonium, fabrication of fresh nuclear fuel using recycled uranium and plutonium. At the same time, all requirements to composition and characteristics of the materials for all operations of the technological cycle are simply regulated. Today, for all reasons, AREVA is the most acceptable company for Ukraine to solve the problems of NFC closure. SE NNEGC Energoatom has already taken the first steps in this direction and made a statement on the possibility of reprocessing SNF from WWER reactors by this company.

It is necessary to explore all issues on manufacturing nuclear fuel using recycled uranium and plutonium for a specific partner.

According to the estimates, the NFC option using the operation of uranium re-enrichment with centrifuged recycled uranium (ReU) ensures fabrication of 5080 FAs for WWER-1000 reactors, including 1085 FAs from recycled uranium with a zero cost and 3995 FAs from recycled uranium obtained during WWER SNF reprocessing at world prices.

In case of re-enrichment of recycled uranium from an external source of ^{235}U , 30114 FAs can be manufactured using recycled uranium, including 6436 FAs from recycled uranium with a zero cost and 23678 FAs from recycled uranium that will be obtained during WWER SNF reprocessing at world prices.

Considering the NFC options with a single-cycle use of recycled uranium, the option where UFPs have a zero cost is considered as an open NFC. The option, in which SNF stored in Ukraine can be reprocessed by Western companies, is considered as a closed NFC, and the economic estimates begin with the SNF storage stage.

For each option of WWER-1000 NFC closure, a coefficient showing the amount of SNF that needs to be reprocessed to produce 1 kg HM of fuel with the use of recycled uranium was preliminarily calculated, which is: 5.93 for ReU; 1 for ReU+ ^{235}U ; 4.18 for MOX fuel.

The cost of UFP is determined by the costs of SNF reprocessing and is distributed in proportion to the content of fissile isotopes in the material.

The cost of storage and disposal of SNF from recycled uranium is assumed to be the same as the cost of these steps for WWER-1000 SNF in an open cycle.

Table 4 provides the economic estimates for the fuel component of electricity generation using recycled uranium and plutonium having a zero cost, and the cost of SNF reprocessing at world prices.

Table 4

Fuel component of the cost of electricity of NFC at zero cost of recycled material and at world prices*, 10^{-3} \$/(kWh)

Stages, steps	NFC option		
	ReU	ReU+ ²³⁵ U	MOX
SNF storage before reprocessing	2.79	0.44	1.85
SNF reprocessing	0 (7.29)*	0 (1.16)*	0 (5.03)*
Costs for production of uranium of required enrichment	2.10	4.80	0.00
Fabrication of FNF from recycled uranium	0.79	0.79	3.13
FNF transportation	0.01	0.01	0.01
SNF transportation	0.18	0.18	0.18
SNF storage	0.60	0.60	0.60
SNF conditioning	1.33	1.33	1.33
SNF disposal	0.26	0.26	0.26
Total	5.27 (15.35)*	7.97 (9.57)	5.51 (12.38)*

*Values in parentheses account for SNF reprocessing at world prices

For the options using recycled uranium in the NFC, the question remains what to do with plutonium. According to the global data, plutonium storage is quite expensive and raises many questions related to safety and non-proliferation.

Taking into account all aspects of the problem, the most attractive NFC option is the one using both recycled uranium and plutonium – MOX fuel for fabrication of fresh nuclear fuel. Practically, this NFC option is the most attractive for implementation in the world. The use of this option will allow to produce 7213 WWER-1000 fuel assemblies from the accumulated SNF, including 1540 FAs from the products returned from the Russian Federation and 5673 FAs from the SNF that will be reprocessed in the future at world prices. Since fuel re-enrichment is done at the expense of plutonium, the remaining recycled uranium can be used in other NFC options. It should be noted that while using MOX fuel, it is necessary to determine the quantity of MOX fuel that can be loaded into reactor – 30%, or 100%. For this purpose, it is necessary to explore both the issues related to reactor physics and the technological tasks on the manufactured fuel composition.

It should be noted that considered options of the use of recycled uranium in the fresh nuclear fuel production (ReU and ReU+²³⁵U) have been technologically elaborated on a commercial scale and are either being implemented or can be implemented with minor improvements by the world's leading companies.

A technology for manufacturing MOX fuel for light water reactors exists in AREVA. More attention has been given in the world to elaboration of the processes of making fuel rods and fuel assemblies with MOX fuel for fast reactors.

Therefore, considering the issues of manufacturing WWER fuel rods and FAs with the use of UFP in practical terms, Ukraine has to identify a chain of partners for fabrication of fuel using recycled uranium, or envisage implementation of these options while establishing its own fuel rod and fuel assembly fabrication plant.

CANDU REACTORS

A working group established by the Ministry of Fuels and Energy of Ukraine in 2007-2008 to address the problems of introduction of CANDU reactors in the structure of Ukraine's NP made a conclusion on possibility of this process, which means that all formal and legal issues can be resolved. Therefore, we will focus only on the economic aspects of the nuclear fuel cycle with CANDU reactors.

When natural uranium is used as fuel, it is necessary to manufacture a large quantity of fuel rods per unit of energy generation, and approximately 5.8 times more SNF is produced as compared with WWER reactors. For an open NFC, this means that the costs for SNF removal from CANDU reactors per 1 kg HM are 5.8 times higher than for WWER reactors. Assumptions that they may be lower for CANDU due to a lower radioactivity have not been proven in practice. Therefore, for the economic assessments performed to compare nuclear fuel cycles with CANDU and WWER reactors, two variants were considered. In the first variant, the cost of the main stages of CANDU NFC was taken to be the same as for WWER NFC (Table 1); in the second variant, the values of the cost of the stages for CANDU NFC (Table 2), which are predicted for future manufacturing processes for SNF management stages of CANDU reactors, were used.

For comparison, Tables 5, 6 show the results of calculations of the economic estimates of the fuel component of electricity generation with CANDU reactors for the following options:

1. Fuel is made of natural uranium (0.71% ²³⁵U).
2. Fuel is made of slightly enriched uranium (1.2% ²³⁵U).
3. Reprocessing of SNF from WWER reactors; recycled uranium is used for manufacturing fuel for CANDU reactors (1.2% Re²³⁵U).
4. Reprocessing of SNF from WWER reactors; recycled uranium and plutonium are used for manufacturing MOX fuel (1.5% (U + Pu)).

Table 5

Fuel component of the cost of electricity for CANDU NFC, 10^{-3} \$/(kWhe) (the same cost of stages as for WWER)

NFC Steps	NFC Option			
	0.71% ²³⁵ U	1.2% ²³⁵ U	1.2%Re ²³⁵ U	1.5% (U+Pu)
NFC storage before reprocessing	-	-	2.11	1.12
Fabrication of FNF from natural uranium	2.53	3.31	-	-
SNF reprocessing	-	-	4.28	5.29
Re-enrichment	-	-	0.31	0.00
FNF fabrication using UFP	-	-	0.64	4.12
FA transportation	0.08	0.04	0.04	0.04
SNF transportation	1.05	0.62	0.62	0.51
SNF storage	3.48	2.06	2.06	1.70
SNF conditioning	7.73	4.57	4.57	3.76
SNF disposal	1.52	0.90	0.9	0.74
Total	16.38	11.50	15.54	17.28

Table 6

Fuel component of the cost of electricity for CANDU NFC, 10^{-3} \$/(kWhe) (estimated cost of stages)

NFC Stages	NFC Option			
	0.71% ²³⁵ U	1.2% ²³⁵ U	1.2%Re ²³⁵ U	1.5% (U+Pu)
NFC storage before reprocessing			2.11	1.12
FNF fabrication from natural uranium	2.53	3.31	-	-
SNF reprocessing	-	-	4.28	5.54
Re-enrichment	-	-	0.31	0.00
FNF fabrication using UFP	-	-	0,64	4,12
FA transportation	0.08	0.04	0.04	0.04
SNF transportation	0.08	0.05	0.05	0.04
SNF storage	0.71	0.42	0.42	0.35
SNF conditioning	3.06	1.88	1.81	1.49
SNF disposal	1.36	0.81	0.81	0.66
Total	7.82	6.44	10.48	13.35

RESULTS

The assessments performed for NFC with WWER reactors show that the simplest technological option of using recycled uranium with a zero cost in the fabrication of fresh fuel consisting in utilization of the stage of uranium re-enrichment, for example, by the gas-centrifuge enrichment operation, provides the best economic effect (ReU). The cost of the fuel component in this case can be 33% lower as compared with the conventional open NFC with natural uranium for WWER reactors. The total real saving for this option when using all recycled uranium with zero cost can reach about \$ 467 million.

Economic estimates of the fuel component of electricity generation when using MOX fuel in WWER-1000 reactors show that at zero cost of initial products (SNF reprocessing in the Russian Federation), the cost of electricity generation is about 30% lower than that for an open NFC. At today's price levels, the use of uranium and plutonium in the NFC with MOX fuel would save Ukraine about \$ 600 million.

In case of future implementation of a closed NFC with SNF reprocessing at world prices and attributing the reprocessing cost to UFP, the assessments show that that the fuel component of electricity generation for all

NFC options will be approximately 18 to 47% higher than for an open NFC. This justifies the lack of will to implement a closed NFC at today's world prices for natural uranium.

The results of assessments performed for the option in which the cost of SNF management stages is assumed to be similar to that of WWER reactors (Table 5) show, that with introduction of CANDU reactors into the structure of Ukraine's NP, the fuel component of electricity production with CANDU reactors which use natural uranium fuel, is much higher than for an open NFC with WWER reactors.

In case of using predicted minimal values of the cost of NFC steps (Table 6) of manufacturing FNF for CANDU reactors, the fuel component of electricity generation for CANDU reactors using natural uranium is comparable to that produced by WWER reactors in an open NFC. If enriched uranium is used, the fuel component for CANDU reactors is approximately 18% lower than for WWER reactors in an open NFC.

CONCLUSION

The functioning of NP in the world is supported with resolving the issues associated with the uncertainty about the final NFC stage - SNF management. Taking benefit of safe and long-term SNF storage, most of the

states using NP are waiting for fundamental decisions on when it will be economically expedient to introduce fast reactors in the NP structure, and further to resolve the whole range of problems associated with NFC, developing and implementing specific closed NFC options. The most important stages of closed NFCs are SNF reprocessing, HLW conditioning and disposal.

As mentioned above, in Ukraine, a decision was made earlier on recycling part of the SNF from WWER reactors. The question is which options of useful fission products management are most economically viable: should they be removed for long-term storage until a decision is made on what to do with them, or should they be used in the NFC with WWER reactors that will continue to be operated in the structure of Ukrainian NP for a long time.

The above results of economic evaluations of the costs of the fuel component of electricity generation for various NFC options show that the cost of electricity is the smallest at a zero cost of reprocessing useful products from SNF. In any case, it is necessary to implement the NFC options with these products in a realistic perspective, primarily the options with recycled uranium. As shown above, the costs of NFC in this case can be approximately \$ 467 million lower than those of an open NFC with WWER-1000 reactors.

At the same time, it must be noted that storage of these products, especially of plutonium, results in changes in the isotopic composition and chemical state. This implies additional costs not only for storage, but also for restoration of performance of materials used for manufacturing FAs for WWER reactors.

If a decision is made on the use of UFP in Ukrainian WWER reactors, the following steps should be taken:

- develop relevant regulatory documents for all NFC stages;
- develop specific NFC options using recycled uranium and plutonium;
- identify partners for manufacturing fresh nuclear fuel using UFP.

As regards introduction of CANDU reactors in the structure of NP of Ukraine, evaluation of the fuel component of the cost of electricity demonstrates that without determining the real value of the stages of SNF management it is impossible to substantiate the economic benefit of the CANDU NFC as compared with the WWER NFC.

In general, regarding the development of NFC in Ukraine, taking into account the capabilities of all SNF management options in the world and the state of SNF from RBMK and WWER reactors stored in Ukraine, it is necessary to elaborate the technologies for conditioning SNF, such as HLW, and address the issues

of searching and substantiation of geological formations for the disposal of HLW.

REFERENCES

1. *Trends in the nuclear fuel cycle Economic, Environmental and Social Aspects*. Nuclear Energy Agency, OECD, Paris. 2. NEA and IAEA, 2001.
2. *The Economics of the nuclear fuel cycle*. Nuclear Energy Agency Organization for Economic Co-Operation and Development, 1994.
3. *Accelerator-driven Systems and Fast Reactors in Advanced Nuclear Fuel Cycles*. Nuclear Energy Agency Organization for Economic Co-Operation and Development. A Comparative Study, 2002.
4. *Generation 4 Roadmap – Report of the Fuel Cycle Crosscut Group*. DOE, 2001.
5. Fetter, Bunn, Holdren. *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel*. Final Report, 1999-2003.
6. Nuclear Fuel Price Indicators. http://www.uxc.com/review/uxc_Prices.aspx
7. *Nuclear Science and Engineering*. 1999, v. 131, N 1, p. 60-71.
8. Hangbok Choi, Won Il Ko. *Economic analysis on direct use of spent pressurized water reactor fuel in CANDU reactors–i: DUPIC fuel fabrication cost*. Korea Atomic Energy Research Institute, P.O. Box 105, Yusong, Taejeon, Korea, 2001.
9. S.V. Begun, S.V. Shyrokov. *Reactors based on CANDU technology // Nuclear and Radiation Safety Journal*. 2012, issue 1(53).
10. A.A. Tretyakov. *Recycling of WWER-1000 SNF at the pilot demonstration center at FSUE “GKhK”: Presentation at the meeting of the Ukrainian-Russian working group on WWER-1000 SNF management*, 2011.
11. *Methodology for calculation of amount and activity of SNF reprocessing products from Ukrainian WWER-1000 NPPs at FSUE “GKhK”*.
12. *Initial data for development of a hardware and technological scheme of the basic technology for reprocessing of WWER-1000 SNF (FSUE “GKhK”, report of FSUE “Radium Institute n. a. V.G. Khlopina” No. 3547-IKT*.
13. A.A. Dubnikov. *Effect of ²³⁶U on the efficiency of multiple use of recycled uranium in WWER fuel // Atomic Energy*. 2015, v. 119B.
14. Yu.S. Fedorov, B.Ya. Zilberman, B.A. Bibichev. *Possibility of solving the problem of SNF management by repeated recycling of REMIX fuel in thermal reactors*. Moscow: “AtomEco-2012”, October 16-17, 2012.

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О ВАРИАНТАХ ЯДЕРНОГО ТОПЛИВНОГО ЦИКЛА УКРАИНЫ

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Существующая стратегия развития атомной энергетики (АЭ) Украины обозначает, по крайней мере, сохранение в дальнейшем объема производства электроэнергии на АЭС примерно эквивалентным производимому на сегодня. Как это сделать, скрывается в общих формулировках, это касается и решения

проблем и задач по ядерному топливному циклу (ЯТЦ). Известно, что ЯТЦ – это основной показатель, определяющий экономику АЭ. Неопределенность видений, какие ЯТЦ необходимо развивать, какие стадии и этапы реализовывать во временной перспективе, затрудняет принятие своевременных решений. В обобщающем виде представлены оценки вариантов затрат ЯТЦ с реакторами типа ВВЭР и CANDU для открытого и закрытого циклов с использованием затрат по этапам, принимаемым на сегодня в мире.

ПРО ВАРИАНТИ ЯДЕРНОГО ПАЛИВНОГО ЦИКЛУ УКРАЇНИ

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Існуюча стратегія розвитку атомної енергетики (АЕ) України означає, принаймні, збереження в подальшому обсягу виробництва електроенергії на АЕС приблизно еквівалентним виробляемому на сьогодні. Як це зробити, ховається в загальних формулюваннях, це стосується і рішення проблем і завдань з ядерного паливного циклу (ЯПЦ). Відомо, що ЯПЦ – це основний показник, що визначає економіку АЕ. Невизначеність бачення, які ЯПЦ необхідно розвивати, які стадії і етапи реалізовувати в часовій перспективі, ускладнює прийняття своєчасних рішень. В узагальнюючому вигляді представлені оцінки варіантів витрат для відкритого і закритого ЯПЦ з реакторами типу ВВЕР і CANDU, з використанням витрат по етапам, що приймаються на сьогодні в світі.