ISSN 0002-306X. Proc. of the RA NAS and NPUA Ser. of tech. sc. 2016. V. LXIX, N 2.

UDC 621.311.22 ENERGETIES

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ASSESSING THE IMPACT OF FUEL CYCLE BACK END OPTIONS ON THE LEVELIZED UNIT ELECTRICITY COST OF THE PRODUCED ELECTRICITY BASED ON THE NUCLEAR FUEL CYCLE IN ARMENIA

An attempt has been made to assess the costs needed for the long-term treatment of the spent nuclear fuel and its impact on the levelized unit electricity cost generated by nuclear units in the case of RA nuclear power development up to 2100. The following cases have been observed wherein the spent nuclear fuel is stored in dry cooling storages on the station platform for 50 years, and afterwards, transferred to a geological disposal or to another country for recycling and final disposal.

Keywords: spent nuclear fuel, nuclear fuel cycle, levelized unit electricity cost, uranium resources, uranium conversion services, geological disposed spent nuclear fuel, reprocessing the spent nuclear fuel.

Introduction. The spent nuclear fuel management is an important part of the nuclear fuel cycle (NFC) development. Nowadays, different options for treatment of the spent nuclear fuel (SNF) are offered. An important factor for selecting a strategy for final SNF management is the economic evaluation that allows a comparative analysis of different scenarios of NFC and/or reveals the influence of the different components of the NFC on the entire fuel cycle cost.

Finding a solution for SNF may determine the direction of implementation of the national strategy for the further development of nuclear power generation. Due to the amounts of the accumulated SNF and the lack of generally accepted solutions for its optimal final management, long-term assessment is necessary to determine the impact on the cost of electricity produced by NPPs in various NFC scenarios.

Common approaches for assessing the impact of the final stage of nuclear fuel cycle on the Levelized Unit Electricity Cost (LUEC) of electricity when considering "idealized model" are presented in the OECD report [1]. It is shown that the assessment of the final stage impact of the NFC requires to determine the value of the entire fuel cycle, including the construction costs of nuclear power plants, nuclear fuel procurement, maintenance, storage and disposal of the spent nuclear fuel. For sensitivity analysis the study considers the options for removal of SNF from the NPP site to another country for reprocessing and final disposal with different transportation types (truck, railway, air transport).

Objectives of the study. The following objectives have been formulated:

- development of a model for NFC options, including;
- the SNF storage at the NPP site;
- the SNF storage at the NPP site and transfer of the SNF from the NPP site to geological disposal;
- the SNF storage at the NPP site and export of the SNF from Armenia with by transportation types (truck, railway, and air transport) for reprocessing and final disposal in another country;
- assessment of the impact of the SNF management cost on the cost of electricity produced by the NPP;
- development of potential recommendations on optimizing the cost of the spent nuclear fuel management, and for sustainable development of nuclear generation in Armenia.

The main goal is to analyse the impact of the NFC options on the LUEC of electricity produced by the NPP in Armenia.

A brief description of armenian energy system

Energy Resources. Hydro resources are the main domestic energy carrier. Their theoretical potential is valued at 21.8 billion *kWh*, with the technically available potential of 7…8 billion *kWh* and the economically sound hydro potential – of about 3.6 billion *kWh*. 1.5 billion kWh of that potential is already applicable, and the implementation of the remaining part is expected during the next 15 years.

Another source of energy in Armenia is wind power. The theoretical potential is assessed to be 1,07 billion *kWh*, the technically available potential in case of 10% of power ratio is about 0,11 billion *kWh*. The implementation of the wind energy potential is expected to be realized during the following 15...20 years.

The potential of solar energy is great. The utilization of that kind of energy, especially with the purpose of thermal energy generation can significantly decrease the need for imported energy carriers. The average annual inflow of solar energy per square unit of horizontal surface is 1 720 kWh/m^2, and one fourth of the republic’s territory is exposed to 1 850 kWh/m^2 intensity of solar energy annually.

The utilization of biomass in Armenia, as a source of energy is not widely spread yet.

The utilization of geothermal resources in Armenia is rather perspective. In case of the positive results of ongoing investigation and potential assessment of geothermal resources as renewable energy resource, it can become attractive either for private investors or for international financial organizations.

The process of investigation of oil and gas availability lasting from 1947 till nowadays, hasn’t revealed any oil or gas mines on the territory of Armenia.

Geological investigations show that there is a certain quantity of fossil fuel on the territory of Armenia, which has no industrial importance for the whole energy sector because its caloricity is rather low, and it can be used for limited demand.

Energy saving is referred to as the own energy reserve. According to the approximate assessment, the application of its full potential can save 20% of the energy consumed. According to the Law on Energy Saving and Renewable Energy, as well as to the programs of its development and implementation, the application of energy saving is of great importance for the country.

Power Sector: The summary of available capacities of power plants in the Armenian Power System is presented in Table 1.

Table 1

Available capacities of the power plants in Armenia

POWER PLANTS	MW
Armenian NPP	407.5
Hrazdan TPP	1110
Hrazdan 5 (gas and steam turbines unit),	440
Yerevan TPP	550
Yerevan CCGT	242
Sevan-Hrazdan Cascade of HPPs	562
Vorotan cascade of HPPs	404
Small HPPs (<30 *MW*)	282
Wind Power Plant	2.6

Armenian demand forecast for 21st century and power technologies considered for investigation. Historically, the average annual growth rate of electricity consumption in Armenia during the last 10 years (2003-2013) was recorded at the level of 3.72%/year. This rate has been accepted as a base rate for

the projection years but with de-escalation rate of "minus" 0.05% per annum. Based on this assumption, the calculated average annual demand growth rate for the whole planning period (up to 2100) is equal to 1.54% per year.

Today, Armenia has signed a long-term swap agreement with Iran according to which Armenia should export electricity to Iran at the level of 6 900 million *kWh* per year instead of the imported natural gas from Iran till 2027. It is assumed that this agreement will be prolonged up to the end of the simulation period. So after 2027, the export to Iran will be kept at the level of the last contractual year. In the same time, it is assumed that the import of electricity from Georgia will be constant - at the level of 2013.

The results of calculations made according to the above assumptions are summarized in Fig. 1.

To ensure all the needs of domestic consumption, as well as to secure obligations of electricity export during this century, around 3340 *MW* of additional capacities will be required. Three types of generation capacities are foreseen for Armenia, namely thermal (natural gas-fired) plants, renewables and nuclear technologies.

As mentioned above, Armenia has very limited domestic sources for electricity generation which are only renewables. According to the Power system development national strategy, all of national economically feasible renewable energy sources (RES) should be utilized in Armenia till 2035. Table 2 provides the list of proven RES and their implementation time-frame. It is assumed that such a structure will be kept up to the end of the whole planning period (the end of 21st century). As it can be seen from table 2 only 714 *MW* of new renewable energy sources from the requested 3340 *MW* additional capacities are available in the country.

Table 2

List of new renewable energy sources

Technology	Installed capacity, *MW*	Annual generation potential, mln. *kWh/year*	Implementation year
Solar PV	40 30	98 32	Up to 2020 Up to 2035
Small HPPs	148	71	Up to 2021
Wind Farms	200	480	Up to 2027
Shnokh HPP	70	270	2021
Loriberd HPP	66	212	2021
Meghri HPP	130	720	2032
Geothermal PP	30	194	2021
Total	714	1960	

Finally, to cover the growing electricity demand and to provide the contractual obligations with Iran, only the implementation of nuclear technologies can be proposed.

So, based on the above-mentioned issues, the structure of electricity generation by different types of power plants for a whole planning period will have a form as shown in Fig. 2.

It is assumed that the VVER-1000 unit will replace the existing Armenian NPP in 2026, and after decommissioning of this unit in 2086, will be put into operation a new VVER-1000 unit. Starting from 2035 six reactors of VBER-300 will come into operation for each decade. The last (sixth) VBER-300 will be introduced into the power system in 2095. The structure of the installed nuclear capacity until 2100 is given in Fig. 3. The total installed nuclear capacity in 2080 will increase to 3,625 MW (2,000 MW - 2xVVER-1000 and 1625 MW -5xVBER-325).

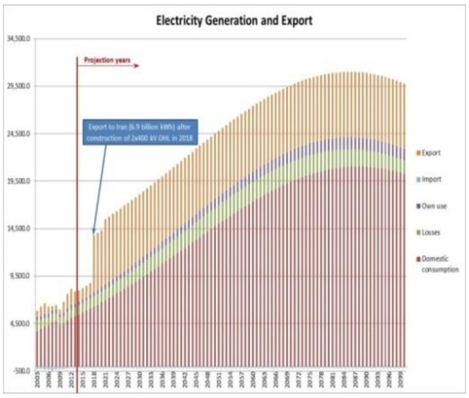

Fig. 1. Structure of electricity generation

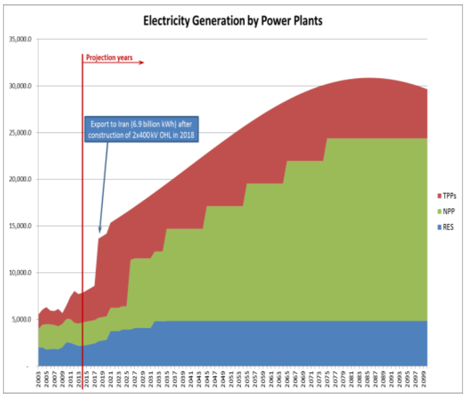

FIG. 2. Generation of electricity by types of power plants

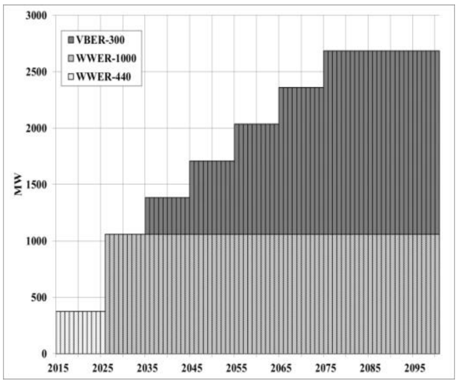

Fig. 3. The structure of Installed Capacities of Reactors

Fuel Cycle and Waste Management. Armenia has no nuclear fuel cycle industry and uses an open nuclear fuel cycle scheme. The ANPP is operating with a three-year fuel cycle. The spent nuclear fuel, before its transfer to the dry storage, is kept in wet nuclear fuel storage – cooling pools in the reactor building.

In 2000, the construction of the first stage of the spent fuel dry storage was completed. The construction was commissioned by the French firm Framatom. The spent fuel dry storage facility has been put into operation and all the transfers of the spent fuel is performed according to the requirements of the license given by the Armenian Nuclear Regulatory Authority. Now, all the volume of the first stage of storage is filled with the spent fuel.

In 2005, an agreement was signed with the French company TN International for construction of the additional three stages of the dry storage facility. The financing was allocated from the State budget of RA. The second stage was completed and put into operation in spring 2008, and the first part of the spent nuclear fuel has been transferred into dry storage. The third stage of the spent fuel dry storage construction started in 2015.

The final spent fuel and high-level radioactive waste treatment and disposal concept will be developed and included in the ANPP Decommissioning Program.

Nuclear fuel cycle options. *Open fuel cycle* – the light water VVER-440 reactor will operate till 2026 and in 2026 – the VVER-1100 will be put into operation. Enrichment of VVER-440 fuel is 3.82%. It is assumed that Unit Capability Factor (UCF) is 72%. The new VVER-1000 unit will be put into operation in 2026 and it is expected that UCF will be 85%.

The LUEC of nuclear generation is determined in the scenarios depending on the final stage in the NFC option. The model structure for the NFC option is presented in Fig. 4.

The option with the Construction of SFDS at the NPP site and after 50 years of the SNF storage, transfer of the SNF to geological disposal or for reprocessing and disposal export of the SNF from the NPP site to another country by different types transportation is presented in Fig. 5. Approximately 2376 tons of SNF will be produced up to 2100. In total, there will be 1592tons of SNF in SFDS collected from all the reactors, considering the export of SNF. The rates of the spent fuel export from dry storage are taken at the level of annual loads for both VVER-440, and VVER-300 reactors and the rates of export for small reactors equal to the SNF supply rate. The SNF export is shown in Fig. 6. Only 784 tons of the SNF will be exported by 2100. The volume of exported the SNF from VVER-1000 will be 403 tonnes for the period up to 2100.

Variable parameters and the variation range of those parameters are shown in Table 3.

Table 3

The parameter value and the range of variation

Parameter	**Value**
Transportation types:	
by truck	100...125 *USD/kgHM*
by railway	40...60 *USD/kgHM*
by air transport	400...700 *USD/kgHM*
Cost of the SFDS construction [4-7]	120...170 *USD/kgHM*
Cost of the geological disposal of SNF [4-7]	500...650 *USD/kgHM*
Cost of the processing without the return of processing waste [8]	1500...2500 *USD/kgHM*

INITIAL DATA

The initial stage of NFC. Uranium resources are considered to be unlimited during the modelling period. The cost of natural uranium is considered at 110 *USD/kg*.

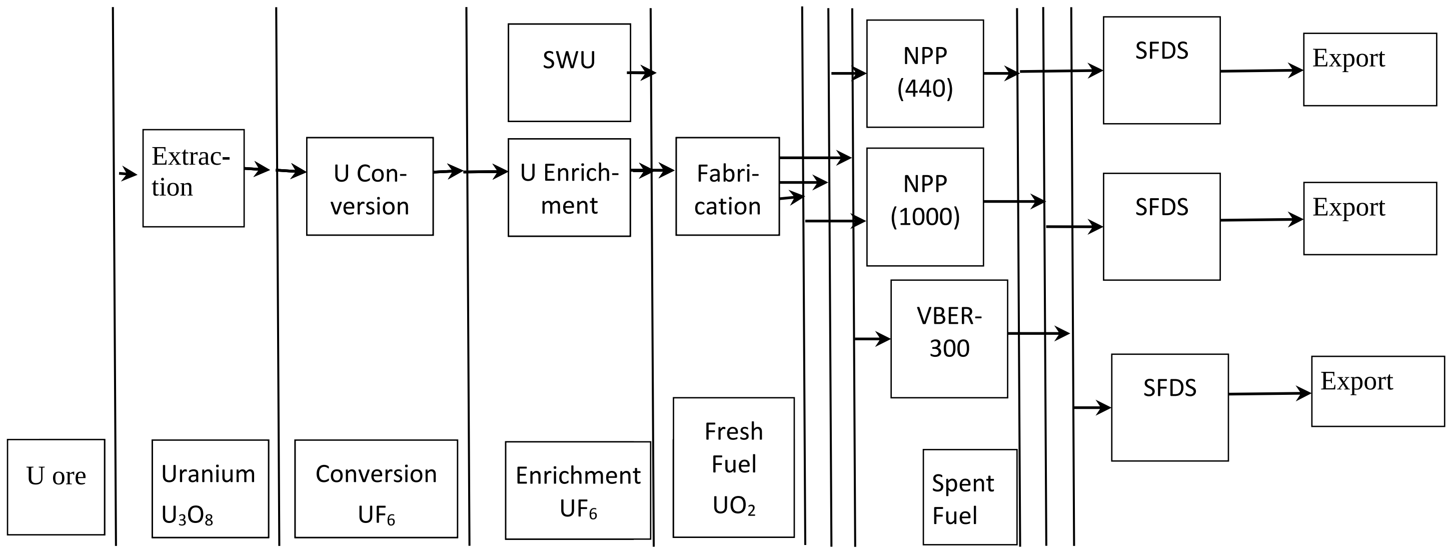

Fig. 4. Structure of the model "Construction SFDS at the NPP site and export of SNF"

Historically, the cost of conversion services varied between 8...5 *usd/kghm* [2]. This value is assumed to be 7.5 *USD/kgHM* in the model. The uranium conversion stage is considered as a service. the process of uranium enrichment is considered as a service with a cost of 160 *USD*/SWU purchased on the world market [2]. It is assumed that the global market for uranium enrichment services is not limited. Tails assay is 0.25%. Fabrication of fresh fuel for light water reactors is considered as service purchased at the price of 300 *USD/kgHM*. The average world prices of fuel fabrication for pressurized water reactors were 250 *USD /kgHM* in 2008 [3]. for the VVER-440 unit real economic data from tariff were used.

Light Water Reactors. Three types of light water reactors are considered in the scenarios: VVER-440, VVER-1000 (Project B-392), and VBER-300. It is planned to commission only two VVER-1000 reactors – the first in 2026 and the second in 2086. A series of small reactors (VBER-300) are expected to be implemented up to the end of the century. The technical and economic data of the considered reactors are present-ed in Table 4 [9].

Table 4

Technical and economic parameters of the reactors used in the model

Parameter	VVER-440	VVER-1000	VBER-300
Heat capacity, MW	1375	3000	912
Electric capacity, MW	375	1060	325
Efficiency, %	32	35	
UCF, %	72	85	85
Fuel enrichment,%	3.82	4.28/4.7	5%
Average burn-up for fuel assemblies, GW·day/t	42.66	48/60	60
The first load, tHM	40.2048 [3]	68.4437/72.844 [1]	22.2144
Annual reload, tHM	8.9856 [3]	20.155/16.088 [2]	4.44
Overnight cost USD/kW	-	5000	5500
Fixed costs, USD/kW	50	50	50
Variable costs, USD/MWh	1	1	1
Operation lifetime, years	13 [4]	60	60
Construction period, years	-	6	5
Fuel fabrication, USD/kg	300	300	300
Construction of SFDS, USD/kg	150	150	150
The cost of disposal of spent nuclear fuel, USD/kg	600	600	600

(1) The first load: Old Fuel - 163 pcs. x 494 kg x 0.85 = 68 443.7 kg; New Fuel - 163 pcs. x 545 kg x 0.85 = 72 844.0 kg, (2) Annual reload: Old Fuel - 36 pcs. x 545 kg x 0.85 = 16 088 kg; New Fuel - 48 pcs. x 494 kg x 0.85 =20 155kg, (3)The first load: 115.2 kg × 349 pcs = 40 204.8 kg, Annual reload: 115,2 × 78 pcs=8985.6 kg; (4) From the starting year (2013) to the decommissioning year (2026) of the modelling.

Different nuclear fuels have been modelled in this study. Their parameters are presented in Table 5 [9].

The following schedule of implementation of new nuclear units (Table 6) is proposed based on the requirement to cover the forecast demand.

Table 5

The value of the nuclear fuel parameters used in the model

Item	VVER-440	VVER-1000	VBER-300
Average enrichment,%	3.82%	4.7%	5%
Burn-up, MW·d/kg	42.66	60.0	60.0
Weight of UO2 in fuel assemblies, kg	115.2	545	N/A
Number ofassemblies in the reactor, pieces	349	163	N/A
Fuel assemblies annual load, pieces	78	36	N/A

Table 6

The schedule of commissioning new nuclear capacities

Reactor	Year of commissioning
VVER-1000	2026, 2086
VBER-300	2035, 2045, 2055, 2065, 2075, 2095

In this assessment, the discount rate is taken at 10% for all the considered scenarios.

Management of the spent nuclear fuel current status

The spent Nuclear Fuel Dry Storage. It is assumed that the storage will be exploited for the whole volume of the SNF from VVER-440 and VVER-1000. The SFDS construction cost is considered to be at the level of 150 *USD/kgHM*.

It is planned that the removal of the SNF of VVER-440 from SFDS will start in 50 years from the date of its loading and before placing the fuel in SFDS is kept for 5 years.

After unloading the spent fuel with enrichment of 4.7% from VVER-1000 it is cooled for 12 years. For the nuclear fuel enriched by 4.28% the cooling time is considered as 5 years. From the cooling pool, the fuel goes to the SFDS to be stored for 50 years.

In the model, enrichment of fuel for VBER-300 is taken equal to 5%; the reactor's SNF is stored in the cooling pool for 12 years, and from the cooling pool it goes to SFDS to be stored for 50 years.

Geological Disposal. The cost of direct geological disposal the spent fuel is given in references [4 - 7]. For modeling the NFC, the geological disposal of SNF for the basic case is considered as a service, with an approximate cost of 600 *USD/kgHM*.

Transportation of SNF. The following three cases of SNF transportation are considered:

- ✓ by railway - 50 *USD/kgHM*;
- ✓ by truck – 112.55 *USD/kgHM;*
- ✓ by air transport – 500 *USD/kgHM.*

SNF export for reprocessing. There is another scenario when considering the possibility of SNF export for reprocessing and disposal without its return to Armenia [8]. Cost of reprocessing and disposal for 1 kg of HM is 2000 *USD/kgHM*.

The simulation time interval. In this study, the starting year of simulation period is 2013, and the ending year is the year of unloading of the last spent nuclear fuel assemblies from SFDS. Due to this, the model does not take into account the investments made before 2013.

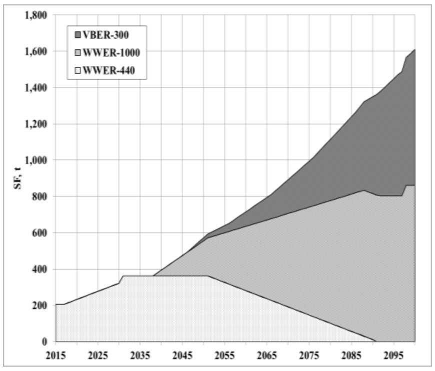

Fig. 5. SNF in Storages Considering Export (Total)

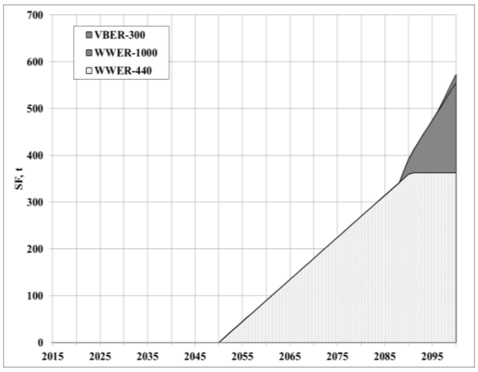

Fig. 6. Export of SNF (Total)

The amounts of SNF exports for VVER-440 and VVER-1000 are limited by the amount of annual loads for the respective reactors. The export of the SNF from VBER-300 is determined by the volume of SNF unloaded from all the reactors in a given year.

LUEC for the option with the construction of SFDS at the NPP site and after 50 years, the SNF for reprocessing and disposal from the NPP site export to another country by air transport or from the NPP site export to geological disposal are presented in Table 7.

LUEC for the option with the construction of SFDS at the NPP site and after 50 years, the SNF for reprocessing and disposal from the NPP site export to another country by different types of transportation are presented in Table 8.

Table 7

The structure of the levelized unit electricity cost (USD/MWh)

Cost Components	Transfer SNF to geological disposal	Reprocessing and disposal export (by air transport) of SNF from the NPP site to another country
Investment component costs	38.78	38.78
Fixed costs	8.97	8.97
Variable costs	0.83	0.83
Uranium price	3.00	3.00
Conversion costs	0.20	0.20
Enrichment costs	3.21	3.21
Fabrication costs	1.60	1.60
SNF management costs	0.21	0.21
Transfer costs	-	0.03
Cost of the processing without the return of processing waste	-	0.11
Cost of the geological disposal	0.03	-
LUEC	56.86	56.96

Table 8

The levelized unit electricity cost in different scenarios, USD/MWh

Export of SNF from the NPP site to another country)	56.94–SNF export by railway transport	56.94 – SNF export by truck	56.96 – SNF export by air transport

CONCLUSIONS

The low sensitivity of the present value of electricity to the modification of the scenarios' conditions is related to the following factors:

- small contribution of the final stage of NFC in the overall structure of the present value;
- small exported amounts of SNF in the period under review;
- an extended period of the SNF removal (until 2150);
- putting off the later export or disposal;
- lack of consideration of SFDS operational costs and geological storage in the model.

In the structure of the present value of electricity, the share corresponding to the final stage of the NFC, is a small part (4%). Changes in the price of the SNF management have an insignificant effect changes in the present value of electricity.

The option with the construction of SFDS at the base conditions is an acceptable solution to the management of the SNF. However, given the need of SNF management after the project period of the storage in the SFDS, the export of the SNF may be more attractive after its discharge from the cooling pool.

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National Polytechnic University of Armenia. The material was received 10.03.2016.

Ս.Ա. ԳԵՎՈՐԳՅԱՆ

ՄԻՋՈՒԿԱՅԻՆ ՎԱՌԵԼԻՔԻ ՑԻԿԼԻ ՎԵՐՋՆԱԿԱՆ ՓՈՒԼԻ ՏԱՐԲԵՐԱԿՆԵՐԻ՝ ԱՐՏԱԴՐՎԱԾ ԷԼԵԿՏՐԱԿԱՆ ԷՆԵՐԳԻԱՅԻ ԲԵՐՎԱԾ ԻՆՔՆԱՐԺԵՔԻ ՎՐԱ ԱԶԴԵՑՈՒԹՅԱՆ ԳՆԱՀԱՏՈՒՄԸ՝ ԵԼՆԵԼՈՎ ՀԱՅԱՍՏԱՆՈՒՄ ՄԻՋՈՒԿԱՅԻՆ ՎԱՌԵԼԻՔԻ ՑԻԿԼԵՐԻՑ

Փորձ է արված ՀՀ-ում միջուկային էներգետիկայի՝ մինչև 2100 թվականը զարգացման դեպքում գնահատել աշխատած միջուկային վառելիքի երկարաժամկետ կառավարման համար պահանջվող ծախսերը և դրանց ազդեցությունը միջուկային էներգաբլոկներում արտադրված էլեկտրական էներգիայի բերված ինքնարժեքի (LUEC) վրա: Դիտարկվել են հետևյալ տարբերակները. աշխատած միջուկային վառելիքը 50 տարի պահվում է կայանի հարթակում՝ չոր եղանակով հովացվող պահեստարաններում, այնուհետև երկարատև պահման համար տեղափոխվում է երկրաբանական պահեստարան կամ այլ երկիր՝ վերամշակման և այդ երկրում երկարատև պահման նպատակով:

Առանցքային բառեր. աշխատած միջուկային վառելիք, էլեկտրական էներգիայի բերված ինքնարժեք, ուրանի պաշար, ուրանի ձևափոխման ծառայություն, աշխատած միջուկային վառելիքի երկրաբանական պահեստարան, աշխատած միջուկային վառելիքի վերամշակում:

С.А. ГЕВОРКЯН

ОЦЕНКА ВЛИЯНИЯ ВАРИАНТОВ КОНЕЧНОГО ЭТАПА ОБРАЩЕНИЯ С ОТРАБОТАННЫМ ЯДЕРНЫМ ТОПЛИВОМ НА ПРИВЕДЕННУЮ СТОИМОСТЬ ЭЛЕКТРОЭНЕРГИИ ИСХОДЯ ИЗ ЦИКЛОВ ЯДЕРНОГО ТОПЛИВА В АРМЕНИИ

Сделана попытка оценить затраты на долговременное обращение с отработанным ядерным топливом и их влияние на приведенную стоимость (LUEC) электроэнергии, произведенной на ядерных энергоблоках при развитии ядерной энергетики в РА до 2100 г. Рассмотрены следующие сценарии: отработанное ядерное топливо 50 лет хранится на территории станции в хранилище, охлаждаемом сухим методом, затем для окончательного захоронения перевозится либо в геологическое хранилище, либо в другую страну для переработки и захоронения.

Ключевые слова: отработанное ядерное топливо, приведенная стоимость электроэнергии, ресурс урана, услуга по конверсии урана, геологическое хранилище отработанного ядерного топлива, переработка отработанного ядерного топлива.