Analysis of the SVBR-100 nuclear fuel cycle by means of the advanced nuclear fuel cycle assessment methodology (ATTR)

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Abstract. The present paper provides the analysis of nuclear fuel cycle of NPP's with SVBR-100 reactor type using the advanced nuclear fuel cycle assessment methodology (ATTR) to ensure non-proliferation of fissile materials and to assess the consumption and saving of uranium recourses by means of IAEA software.

Key Words: RepU, SVBR-100, ATTR.

1. Introduction

Among the challenges facing the sustainable nuclear power development are the security of the fuel supply, spent nuclear fuel (SNF) management and risks of proliferation. To address these issues in 2010 a Federal Target Programme (FTP) "Nuclear power technologies of new generation" aimed at closing nuclear fuel cycle (NFC) and increasing the efficiency of using uranium resources was adopted [1]. In the FTP the significant consideration is given to NFC closing with the use of fast reactors, including BN-1200, BREST-300, SVBR-100 and technological enhancement of non-proliferation regime [2].

SVBR-100 cooled by lead-bismuth eutectic alloy could achieve a relatively simple design and low reactor cost without compromising safety [3]. In the current design option uranium fuel with average enrichment of 16.5 % is considered [4]. Lower capital costs and requirements to grid transmission capacity compared to GW class reactors make SVBR-100 an attractive power supply option for remote areas with lack of grid infrastructure. Needless to say, proliferation resistance of SVBR-100 fuel cycle is a necessary prerequisite to its expansion in emerging nuclear countries.

Traditionally, proliferation resistance of fissile materials is increased by denaturation. In the case of plutonium, denaturation involves increasing the fraction of even isotopes of ^{238}Pu and ^{240}Pu, leading to higher power density in fabricated fuel (due to ^{238}Pu) and spontaneous fission neutrons (due to both isotopes). The fraction of ^{238},^{240}Pu even isotopes in the plutonium composition can be increased by recycling of neptunium and trans-plutonium elements (TRPu) along with uranium [5]. Technology for fabrication of oxide fuel with initial TRPu or/and neptunium doping still needs to be matured. The use of reprocessed uranium to form proliferation-resistance fuel cycle for SVBR-100 seems to be more realistic option for meeting the non-proliferation requirements.

Along with denaturation of plutonium self-generated in SVBR-100, the use of reprocessed uranium increases proliferation-resistance of enriched uranium through the presence of even isotopes ^{232},^{236}U. Decay product of ^{232}U -^{228}Th forms non-volatile fluorides inhibiting enrichment process needless to say about hard gamma radiation (decay product ^{208}Tl provides gamma radiation with energy 2.614MeV) [6,7]. The difference in atomic masses of isotopes

^{235}U and ^{236}U is only 1 amu and this makes it much more difficult to separate them thus increasing the required amount of separative work units (SWU) to produce weapons-grade material (energy-grade quality 15%) compared to separation of ^{235}U and ^{238}U [8].

This paper deals with the analysis of the isotopic composition in SVBR-100 spent fuel to enhance proliferation resistance of the SVBR-100 fuel cycle and to investigate the possibilities of using reprocessed uranium with increased initial content of ^{236}U. Moreover, it analyzes the nuclear fuel cycle of NPP's with SVBR-100 reactor type using the advanced nuclear fuel cycle assessment methodology (ATTR) to ensure non-proliferation of fissile materials and to assess the consumption and saving of uranium recourses by means of IAEA software.

2. MODELLING ISOTOPIC COMPOSITION

The isotope composition analysis is based on fuel burnup modelling with the computer code SERPENT-1.17 [9]. An essential step of the work is bench-marking of the code SERPENT-1.17 using the available data on the isotopic composition of SVBR-100 SNF [4]. Within this task, characteristics of SVBR-100 SNF were determined in a cell approximation. Specification of an elementary cell used in the calculation is presented in Table I.

TABLE I. SPECIFICATION FOR AN ELEMENTARY CELL FOR REACTOR SVBR-100

Parameter	**Value**	
Enrichment by uranium-235% (average)	16.5	
Fuel composition density, g/cm3	10.6	
Outer diameter of fuel pellet, cm	1.12	
Outer diameter of cladding, cm	1.2	
Lattice pitch, cm	1.35	
Burnup, GW·d/t HM	64	
Fuel temperature, K	1274	
Fuel rod cladding temperature, K	793	
Coolant temperature, K	763	
Makeup of steel EL823, %	Fe	85
	Cr	12
	Si	3
Coolant makeup, %	Pb	44.5
	Bi	55.5

The Table II includes the nuclide composition of uranium and trans-uranium elements in SVBR-100 SNF modelled with SERPENT-1.17 as compared with REAKTOR-GP [10]. As can be seen, the results are in good agreement and difference does not exceed 8% for the key uranium and $^{238,239,240}Pu$ isotopes. However, for $^{241,242}Pu$ the deviations are significant, and it is caused by the different nuclear data libraries applied for calculations. A discrepancy in the amount of ^{234}U isotope in SNF can possibly be explained by the difference in its initial amount in fresh fuel applied for these two cases. Ref.4 does not specify ^{234}U content as an input for REAKTOR-GP.

TABLE II. COMPARISON OF ISOTOPIC COMPOSITIONS IN SVBR-100 SNF MODELLED BY SERPENT-1.17 AND REAKTOR-GP

Isotope	**REAKTOR-GP [kg] [4]**	**SERPENT-1.17 [g/t HM]**	**Div. [%]**
234U	9.85E+00	8.749E+02	-22.526
235U	9.41E+02	1.001E+05	-2.261
236U	1.18E+02	1.264 E+04	-1.574
238U	7.22E+03	7.860 E+05	0.037
238Pu	8.14E-01	8.328 E+01	-6.383
239Pu	3.31E+02	3.649 E+04	1.285
240Pu	1.64E+01	1.620 E+03	-7.964
241Pu	5.3E–01	4.523 E+01	-27.536
242Pu	1.37E–02	1.039 E+00	-36.214

3. EFFECT OF ^{236}U DOPING ON FUEL CHARACTERISTICS OF SVBR-100

Enrichment of reprocessed uranium leads to accumulation of significant amounts of ^{234}U and ^{236}U, necessitating compensation of their presence in fresh fuel. The ^{234}U isotope, even though causing a reduction in the initial fuel reactivity, in the process of irradiation is converted into a fissile ^{235}U. The compensation of ^{234}U is pertinent only for heavy water reactors with a small reactivity margin [11]. For other reactor types, it is ^{236}U that determines the necessary compensation since its neutron capture cross-sections are prominently higher compared to that of ^{238}U (Table III). Dynamics of uranium isotopic composition as a function of recycling was analyzed with the use of a methodology described in Ref.8.

TABLE III. ^{236}U, ^{238}U capture cross-sections for different neutron energy

Isotope	**0.0253-eV**	**Res.Int.**	**1MeV**
^{236}U	5.123 (b)	353.4 (b)	0.149 (b)
^{238}U	2.683 (b)	275.6 (b)	0.136 (b)

Fig. 1 shows the neutron multiplication factor (k_{inf}) as a function of fuel burn-up in SVBR-100 and initial doping of isotope ^{236}U. Its presence in the fresh fuel results in a slight change in k_{inf} in the beginning of cycle. One of the objectives of this study is to analyze the compensation coefficient (k) of the initial amount of ^{236}U for fabricating the fuel of equivalent enrichment. According to Ref.8, the equivalent content of ^{235}U in enriched reprocessed uranium fuel (ERU-fuel) is estimated as follows:

$$^{235}U_{ERU}(\%) = {}^{235}U_{N}(\%) + k\cdot{}^{236}U_{ERU}(\%) \quad (1)$$

where $^{235}U_{ERU}(\%)$ is the equivalent content of ^{235}U isotope in *ERU*-fuel; $^{235}U_{N}(\%)$ is the content of ^{235}U in enriched natural uranium fuel (*ENU*-fuel); *k* is the compensation coefficient of the initial amount of ^{236}U isotope; $^{236}U_{ERU}(\%)$ is the content of ^{236}U isotope in *ERU*-fuel.

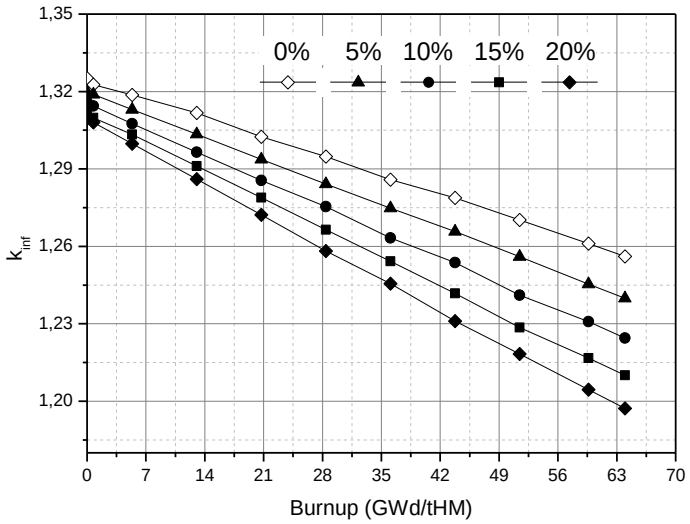

FIG. 1. k_{inf} as a function of SVBR-100 fuel burnup (without ^{236}U compensation).

For analysis of the ^{236}U compensation the authors selected the coefficient fitting criterion corresponding to the identical burn-ups of ERU- and ENU-fuels at a fixed value of k_{inf} at the beginning of the fuel cycle ($k_{inf} = 1.33$).

The effect of the ^{236}U presence in fresh fuel on the compensation coefficient is shown in Fig. 2. An increase of the ^{236}U content in the reprocessed uranium composition leads to reduction in the compensation coefficient required. For example, in order to fabricate fuel of equivalent enrichment from reprocessed uranium with 5% of ^{236}U, the compensation coefficient is to be k=0.03, while for 20% k=0.024, leading to an increase in the initial fuel enrichment by 0.15% and 0.48%, respectively.

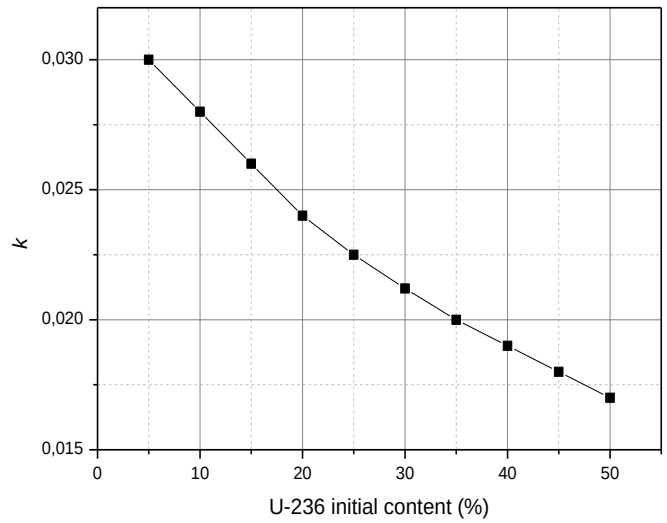

FIG. 2. Compensation coefficient (k) as a function of ^{236}U content in fresh fuel of SVBR-100

This means that using the reprocessed uranium for SRBR-100 does not require the increase in the average fuel enrichment with respect to ^{235}U by more than 20% (which is one of the IAEA criteria for fuel cycle proliferation-resistance). With increasing the initial presence

of ^{236}U by more than 50% in fresh fuel the compensation coefficient k practically does not change and remains at the level k=0.062.

However, replacement of the fertile isotope ^{238}U by ^{236}U in fresh fuel reduces in-core plutonium breeding, which leads to a change in k_{inf} at the end of irradiation cycle. Fig. 3 shows a relationship of the neutron breeding ratio for ENU fuels with compensation of ^{236}U isotope. The presence of 20% ^{236}U in fresh fuel decreases k_{inf} at the end of the irradiation cycle by 0.04 of relative units, which is not critical and can be compensated by moving the control rods of the reactor [4]. It should be stressed that the replacement of ^{238}U by ^{236}U has impact on the reactivity coefficients, however, the issues of safety of using reprocessed uranium with increased ^{236}U content is beyond the scope of this paper.

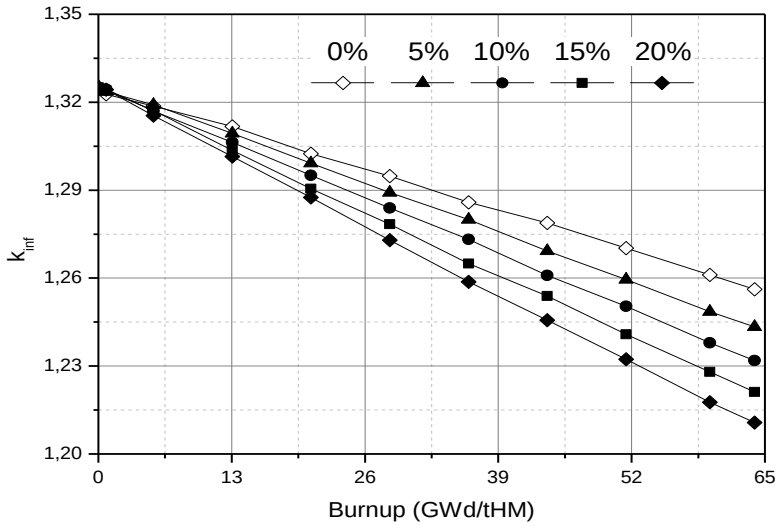

FIG. 3. k_{inf} as a function of burnup (with ^{236}U compensation) in SVBR-100

4. REDUCING ATTRACTIVENESS OF REACTOR-FORMED PLUTONIUM

A decreased content of the fertile isotope ^{238}U in ERU fuel and involvement of ^{236}U in conversion chain result in a prominent reduction of self-generated plutonium and an increase in the fraction of ^{238}Pu (Fig. 4). The objective of this study is to analyze the isotopic vector of ERU fuel, in particular, the required amount of ^{236}U sufficient to breed plutonium which would be unattractive for diversion. Table IV shows isotopic vectors of self-generated plutonium reference burnup (64 GWd/tHM) as a function of the initial ^{236}U doping. The initial doping of more than 20% of ^{236}U results in the ^{238}Pu fraction of more than 6% that makes it impossible manufacture explosive device due to melting of a chemical explosives in implosion type device.[5] As can be seen (Table IV, Fig. 5), the presence of 10% and 25% of ^{236}U in fresh fuel decreases breeding of plutonium by 15% and 35%, respectively.

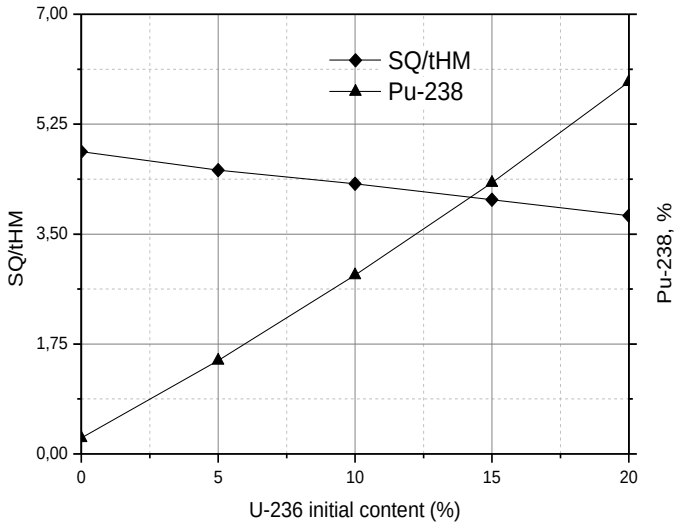

FIG. 4. Significant Quantity (SQ) and ^{238}Pu isotope in the plutonium vector as a function of ^{236}U initial quantity in SVBR-100 fuel.

TABLE IV. PU ISOTOPIC VECTOR AS A FUNCTION OF INITIAL DOPING OF ^{236}U

Isotope	**Initial content of ^{236}U in fuel**					
	0%	**5%**	**10%**	**15%**	**20%**	**25%**
^{238}Pu	0.21	1.51	2.86	4.28	5.81	7.48
^{239}Pu	94.84	93.81	92.73	91.50	90.18	88.71
^{240}Pu	4.83	4.58	4.34	4.13	3.93	3.73
^{241}Pu	0.11	0.10	0.095	0.088	0.081	0.07
^{242}Pu	3.53E-3	3.12E-3	2.77E-3	2.92E-3	2.21E-3	1.97E-3
Pu_{tot} [kg/t HM]	38.0	35.1	32.4	29.8	27.3	24.8

5. REDUCING ATTRACTIVENESS OF REACTOR-FORMED PLUTONIUM

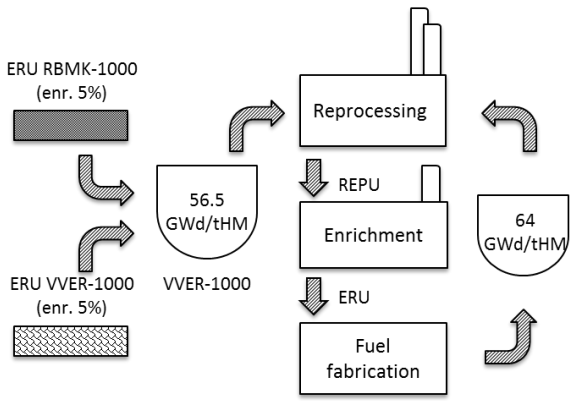

FIG. 5. Fuel cycle of the reactor SVBR-100 based on reprocessed uranium.

As shown above, the initial presence of 20% or more of ^{236}U in the SVBR-100 fresh fuel vector enables to breed proliferation-resistant plutonium. However, uranium isotope separation and subsequent doping of ^{236}U to fresh fuel is extremely sophisticated. For setting up a proliferation-resistance fuel cycle for SVBR-100, two strategies were evaluated based on the reprocessed uranium from VVER-1000 and RBMK-1000 as a source fuel material for SVBR-100.

Fig. 5 illustrates these options. In the first stage, the reprocessed uranium from VVER-1000 or RBMK-1000 SNF is used as fresh fuel for VVER-1000 with the equivalent enrichment 5% with respect to ^{235}U (*ERU 5%).* After irradiation, the VVER-1000 SNF is supplied to a nuclear fuel reprocessing plant, uranium enrichment plant and SVBR-100 fuel fabrication plant. The associated uranium isotopic compositions are summarized in Table V. As one can see, ERU made of RBMK-1000 SNF reveals very high content of ^{236}U.

TABLE V. Isotopic composition of ERU fuel of reactors VVER-1000 and SVBR-100.

	Source fuel			
	VVER-1000 SNF		**RBMK-1000 SNF**	
Isotope	**VVER-1000**	**SVBR-75/100**	**VVER -1000**	**SVBR -75/100**
234U	2.53E-02	2.43E-1	1.76E-01	3.22E-01
235U	5.37E+00	17.65E+00	6.12E+00	18.57E+00
236U	1.23E+00	17.85E+00	4.31E+00	31.88E+00
* the isotopic vector of VVER-1000 and RBMK-1000 spent fuel taken from Ref.12				

6. PROLIFERATION RESISTANCE ASSESSMENT FOR THE FUEL CYCLES OF FAST REACTORS

One of the key stages of the SVBR-100 nuclear fuel cycle research is a proliferation resistance analysis of the uranium and plutonium fractions both for the fuel based on the enriched natural uranium and for the fuel with the initial content of isotope U^{236} equal to 20%. This analysis was conducted by means of the nuclear fuel cycle assessment methodology ATTR.

The equation describing the methodology applied, taking into account technological difficulties, can be represented as follows:

$$ATTR = \frac{\alpha_{max}^2 \cdot \Delta k_{max}}{BCM \cdot DH \cdot DR} \cdot P_{ing} \quad (2)$$

where α – Rossi alpha coefficient;

BCM – bare critical mass of the material;

DH – decay heat;

DR – dose rate;

P_{ign} – the probability that the neutron chain reaction will not start before full yield is guaranteed.

The probability of the full yield and that the neutron chain reaction will not start can be calculated as follows, according to the formula proposed in [14]:

$$1-P(t<t_i^{crit})=\exp\left[-\frac{1}{2}N(t_0-90l_{eff})\right] \quad (3)$$

where t_0 – explosive device material holding period;
l_{eff} – prompt neutrons lifetime;
N – neutrons per second.
Thus, the equation (2) can be rewritten as follows:

$$ATTR=\frac{\alpha_{max}^2\cdot\Delta k_{max}}{BCM\cdot DH\cdot DR}\cdot exp\left[-\frac{1}{2}N(t_0-90l_{eff})\right] \quad (4)$$

The value of the necessary separative work units is an important factor for uranium along with the difficulties presented in the formula, which arise when manufacturing explosive device. Thus, the formula for uranium is:

$$ATTR=\frac{\alpha_{max}^2\cdot\Delta k_{max}}{BCM\cdot DH\cdot DR\cdot SWU}\cdot exp\left[-\frac{1}{2}N(t_0-90l_{eff})\right] \quad (5)$$

where SWU – separative work units, necessary to enrich uranium to the weapons-grade level. The SWU necessary to enrich natural uranium containing isotope ^{235}U is assumes up to 90% as a standard. The isotopic content of ^{235}U in tails is assumed equal to 0,3%. Accounting for the material self-protection can be carried out by means of the normalization of the radiation dose from the bare critical mass by the self-protection level value (SPL – Self Protection Level) [15].

The comparison of the uranium fractions attractiveness for the SVBR-100 fresh and spent nuclear fuel is shown in Fig. 6. The analysis showed that the fresh and irradiated fuel materials with the doping of 20% U^{236} and initial enrichment of 16.5% are less attractive for the shift to manufacture an explosive device.

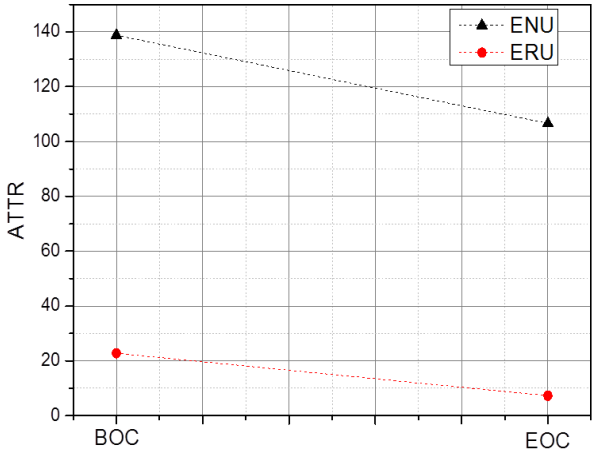

FIG. 6. Comparison of the uranium fractions attractiveness of the SVBR-100 fresh and spent ENU and ERU fuel.

For plutonium the ATTR value can be written taking into account emerging difficulties and, as in the case of uranium, the normalization is performed on the ^{239}Pu, which is more attractive in terms of the explosive device manufacturing.

$$ATTR = \frac{\alpha_{max}^2 \cdot \Delta k_{max}}{BCM \cdot (\frac{DH}{DH_{Pu}}) \cdot (\frac{DR}{DR_{Pu}})} \cdot exp\left[-\frac{1}{2} N(t_0 - 90 l_{eff})\right] \quad (6)$$

The table VI shows parameters of the plutonium fraction of the SVBR-100 irradiated ENU and ERU fuel used for the analysis, as well as the ATTR values at the end of the nuclear fuel irradiation. As shown in the Fig. 6 and in Table VI, the involvement of reprocessed uranium in the SVBR-100 nuclear fuel cycle significantly reduces the attractiveness of nuclear fissile materials at the beginning and end of the fuel irradiation.

Table VI. Parameters of the plutonium fraction of the SVBR-100 irradiated ENU and ERU fuel.

Material	BCM	DH	SNF	Δk	PLT	ATTR
Pu(ENU)	11,3	3,8E+01	2,53E+07	0.4641	2,31E-09	99,35
Pu(ERU)	11,0	4,1E+02	2,50E+07	0.4515	2,28E-09	1,77

7. SAVING OF NATURAL URANIUM

To assess the consumption and saving of uranium resources two options for the fuel cycle were considered (Fig. 7 and 8). The Case A represents fuel cycle based on natural uranium, Case B illustrates fuel cycle based on the reprocessed uranium extracted from the VVER-1000 spent fuel.

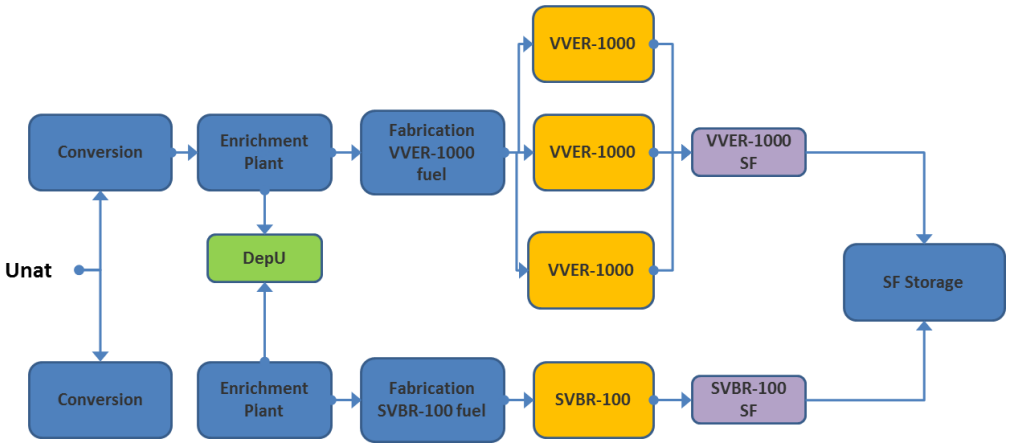

FIG. 7. Scheme of nuclear fuel cycle in case of natural uranium consumption for SVBR (Case A).

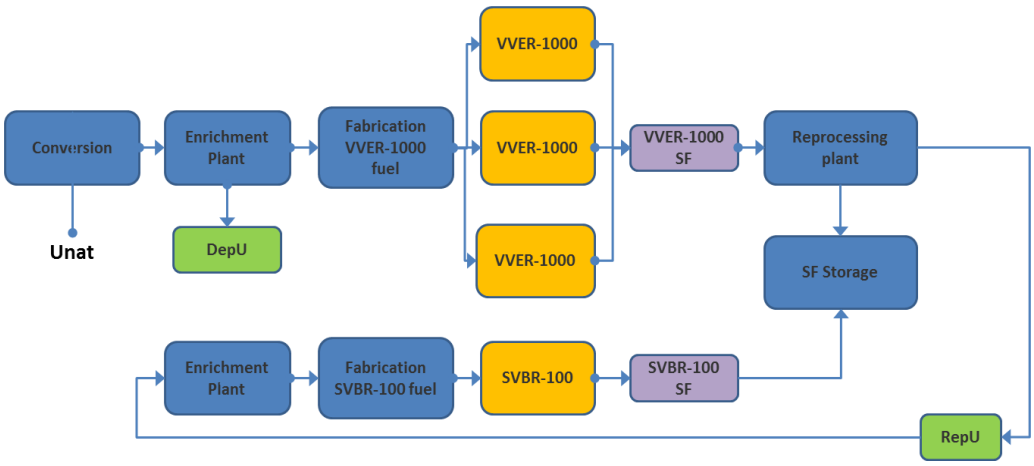

FIG.8. Scheme of nuclear fuel cycle in case of reprocessed uranium consumption for SVBR (Case B).

The IAEA MESSAGE energy planning tool was used to simulate materials flow [16]. The results analysis showed that in case of involvement reprocessed uranium from spent nuclear fuel of VVER-1000 reactors in the fuel cycle of SVBR-100 reactor, the saving of natural uranium consumption is ~10% for all reactor lifetime (Fig. 9)

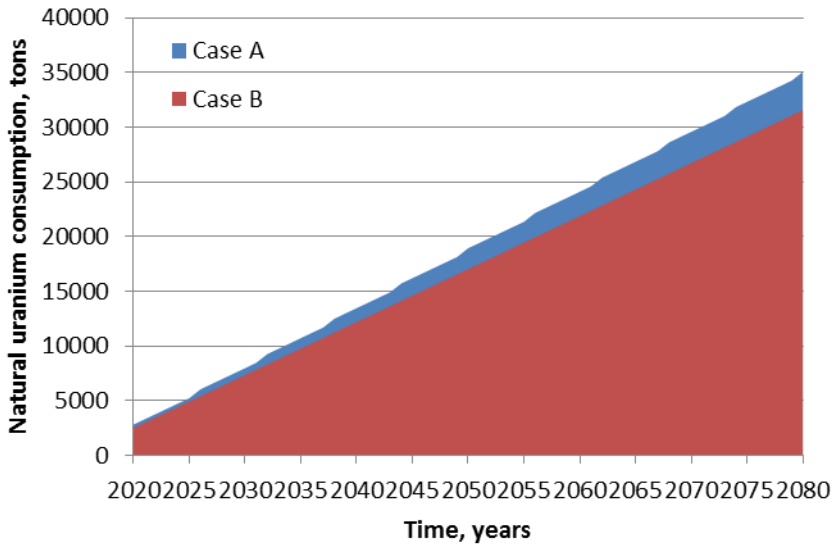

FIG. 9. Natural uranium consumption of SVBR-100.

8. CONCLUSIONS

The use of reprocessed uranium with the increased content of ^{236}U in the fast reactor fuel cycle makes a minor effect on the fuel reactivity and requires little compensation efforts. On the other hand this reduces plutonium generation and enhances its proliferation resistance through increasing the amount of even plutonium isotopes. The analysis performed in the present paper reveals that the RBMK-1000 spent fuel seems to be a

preferable source to set up a proliferation resistant fuel cycle for SVBR-100. The analysis of the SVBR-100 fuel cycle with the reprocessed uranium involvement showed a decrease in the fissile materials attractiveness of fresh and irradiated fuel in terms view of the ATTR methodology, as well as saving of natural uranium consumption ~10% for the whole reactor lifetime.

9. References

[1] Federal Target Programme "Nuclear power technologies of new generation for the period 2010 – 2015 and until 2020". Available at: http://www.businesspravo.ru/Docum/DocumShow_DocumID_163706.html

[2] ADAMOV E.O. "Breakthrough in nuclear power: Closed nuclear fuel cycle with inherent safety " – Materials of "Atomexpo-2012". Available at http://2012.atomexpo.ru/material2012/06.06.2012

[3] RYZHOV S.B., STEPANOV V.S., KLIMOV N.N., ZRODNIKOV A.V., TOSHINSKY G.I., KOMLEV O.G.. Innovative design of SVBR-100, Problems of Atomic Science and Technology. NPP Safety series. 2009, issue 24, pp. 5-7.

[4] VORONKOV A.V., SYCHUGOV E.P., DEDUL A.V., KALCHENKO V.V.,NIKOLAEV A.A., RAKSHUN E.V. Calculation of SVBR-100 life time considering motion of control rods and shim rods. Problems of Atomic Science and Technology,. NPP Safety series, 2009, issue 24, pp/ 38-43.

[5] Kessler G. Plutonium Denaturing by 238Pu. Nuclear Science and Engineering., vol. 155, no. 1, January 2007, pp. 53-73.

[6] KANG J., VON HIPPEL F. N. U-232 and the Proliferation-Resistance of U-233. Spent Fuel Science & Global Securit,, Vol. 9, pp. 1-32, 2001.

[7] KRYUCHKOV E., APSE V., GLEBOV V., KRASNOBAEV A., SHMELEV A. Enriched uranium with doping of 232U isotope: proliferation resistance, Nuclear Power, 2007, issue.4, p. 93.

[8] DIACHENKO A., BALAGUROV NA., ARTISYUK V. Use of reprocessed uranium with high burn-up, Nuclear Power, 2012, issue 1, pp. 135

[9] LEPPÄNEN, J. (2010d) "Serpent Monte Carlo Reactor Physics Code." In proc. 20th AER Symposium on VVER Reactor Physics and reactor safety, Espoo, Finland, Sept. 20-24, 2010.

[10] VORONKOV A.V., Golovkov S.L. "System facilities of "REAKTOR-GP" software – Problems of Atomic Science and Technology, 2009, issue 24, pp. 19-29.

[11] ELLIS RONALD J. Prospects of Using Reprocessed Uranium in CANDU Reactors, in the US GNEP Program. Oak Ridge National Laboratory, PO Box, Oak Ridge, TN 37831-6172. 2008.

[12] TATAUROV A., KVATOR V. R&D Report. Calculated-experimental studying nuclide composition of SNF from VVER-440, VVER-1000 and RBMK-1000. RNC "KI", 2002 (in Russian).

[13] MARK, J.C., 1993. Explosive properties of reactor-grade plutonium. Sci. Global Secur. 4, 111–128.

[14] DEVOLPI, A., 1979. Proliferation, Plutonium and Policy. Pergamon Press, New York

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, The physical Protection of Nuclear Materials and Nuclear Facilities, INFCIRC/225/rev.4, IAEA (1999).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Systems Modelling with MESSAGE: A user's Guide, IAEA Nuclear Energy Series No. NG-T-5.2