On the problems of reusing reprocessed uranium by enrichment in schemes based on ordinary cascades

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Abstract. The problem of spent nuclear fuel attracts considerable attention while its quantity is accumulating worldwide. The problem of long-term supply of the fresh fuel also remains important. One of the strategies to solve both problems is reusing the spent nuclear material. The uranium, in this way, could be recycled multiple times in light-water reactors. In order to recycle the uranium, it is extracted from the irradiated fuel during the reprocessing and then enriched in $^{235}$U, taking into account the limitations on reactor-born isotopes $^{232,236}$U in the final product. The only way to do this is enrichment in cascades of gas centrifuges. However, not every cascade scheme is able to re-enrich the uranium for multiple recycles, utilizing the whole amount of uranium extracted from the irradiated fuel each time. This study shows that configurations based on ordinary three-flow cascades could not be used for this purpose. In particular, we have shown that starting from the second uranium fuel cycle, such schemes are no longer able to reclaim the necessary proportion of the reprocessed uranium.

1. Introduction
The risks and costs of storing the growing inventory of spent fuel will continue to increase; and in the absence of an end point, it will eventually become a significant burden [1]. The limitation of natural uranium is also an obstacle for nuclear energy because, for today, only about 8 megatonnes can be extracted with the price for 1 kg not higher than 260 $ [2]. Even the fact that the worldwide amount of uranium resources on the globe is estimated as $\approx 58$ megatonnes, (where about 80% are unconventional resources) impose long-term constraint on the nuclear industry [1].

Spent fuel recycling could be one of the options to avoid these negative effects due to these properties of the reprocessed uranium (RepU):

(i) Uranium recovered from the spent nuclear fuel (SNF) makes up the majority of its content;
(ii) RepU contains more fissile $^{235}$U than natural one.

Thus, spent fuel reprocessing could provide additional fissile resource for nuclear power plants and decrease the amount of high-level waste. However, the spent fuel reprocessing is difficult, so not many countries have production capacities to do it. Even among global nuclear leaders, only a few countries, such as Russia, France, Japan, decided to reprocess the SNF to close the nuclear fuel cycle.

The next operation to return uranium to the fuel cycle is to produce low-enriched uranium (LEU), which could be used in a light-water reactor (LWR) – the type of power reactor that
dominates worldwide. As we need to raise the level of $^{235}$U, the possibility of reusing the uranium depends on separation technology – cascades of gas centrifuges \[3, 4\]. The major restrictions here are caused by reactor-born $^{232,236}$U and an order of magnitude higher concentration of $^{234}$U than in the NatU. The $^{236}$U acts as a parasitic neutron absorber that inhibits a chain reaction and should be compensated according to equation 1, where $C_{235\text{eq.}}$ stands for the equivalent of $^{235}$U concentration needed to be reached in the final product, with the surplus of $^{235}$U, which depends on $^{230}$U presence ($f(C_{\text{Product}})$), to the initially required concentration of $^{235}$U in LEU product, that is $C_{235\text{Product}}^P$ \[5\]. In our case $f(C_{\text{Product}}) = RCC \times C_{236}^P$, where $RCC$ equals to 0.29.

\[
C_{235\text{eq.}} = C_{235\text{Product}}^P + f(C_{\text{Product}})
\] (1)

The $^{232}$U is a particularly dangerous source of radiation pollution due to intense gamma radiation (2.6 MeV) emitted by a short-lived daughter $^{208}$Tl \[6\]. $^{232,234}$U add detrimental alpha particles to the uranium hexafluoride gas used in the uranium enrichment process \[7\]. As a result, the international specifications, such as an ASTM, restrict the amount of $^{232,234,236}$U in commercial LEU. And as these isotopes are lighter than the prevailing $^{238}$U, they tend to accumulate at the same side of the cascade as the desired $^{235}$U, when the abundant $^{238}$U goes to the other side.

This problem makes it difficult to use an ordinary three-flow cascade for uranium enrichment (figure 1) – a cascade of gas centrifuges (triangle in figure 1), consisting of several stages to achieve the required concentration of $^{235}$U in the LEU product \[8, 9\]. This cascade has 3 external flows: 1) Feed – mixture input to be separated into the cascade; 2) Product -- the flow enriched in $^{235}$U; 3) Waste – the flow depleted in $^{235}$U.

Figure 1. Ordinary enrichment cascade. Figure 2. Cascade with terminal dilution of enriched RepU (Scheme 1).

In the general case, such a cascade does not allow enrichment of reprocessed uranium with a simultaneous correction of its isotopic composition – the concentrations of even-numbered uranium isotopes \[10\]. An exception may be compositions with a relatively low initial content of even isotopes, which does not fit for modern light-water reactors.

To make use of the reprocessed uranium, the necessary modification of the ordinary cascade (figure 1) has been proposed \[5, 11, 12\]. Such schemes are based on preliminary or subsequent RepU admixing – to the feed or product flow, or final dilution of enriched RepU \[13\]. These
adjustments were the primary steps to enrich the reprocessed uranium in order to involve it in the nuclear fuel cycle.

However, to reach sustainable reuse of fissile materials and to avoid accumulation of the irradiated nuclear fuel, it is reasonable to produce the same amount of reactor-quality LEU as the amount of used fuel allocated for this operation. In this way, as the uranium makes up ≈93% of SNF, each kilogram of fresh LEU should be produced from ≈0.93 kg of the RepU to be utilized [14].

This article evaluates the applicability of the simplest modifications of an ordinary cascade to solve the problem of repeated uranium recycling. In other words, the article investigates mass transfer in cascades based on ordinary cascade designed for enrichment of reprocessed uranium in order to assess if they are capable to solve the problem of returning the whole amount of reprocessed uranium to the nuclear fuel cycle in the regime of multiple recycling when the isotope composition is degrading each cycle. These schemes have additional input of natural uranium to dilute unwanted $^{232}$U to meet standard fresh LEU requirements [15]. At the same time, the reasons for the emergence of difficulties with the enrichment of reprocessed uranium with the simultaneous fulfillment of the conditions for even-numbered isotopes and the 1:1 use of the RepU using such schemes are revealed. Then, a method for a priori assessment of the cascade’s ability to utilize the entire amount of irradiated uranium is described. In the next section, the simplest schemes for enrichment of reprocessed uranium will be analyzed.

2. Materials and methods

Let us consider each of the proposed modifications of an ordinary cascade for enrichment of RepU separately.

2.1. Examined schemes

Scheme 1 (figure 2) is one of the simplest possible modification of ordinary cascade which can be used to enrich reprocessed uranium. It enriches RepU in $^{235}$U to a higher level than it is required in the final product, and this intermediate product – $P_0$ is then blended with NatU (or the prepared in advance LEU) to dilute the $^{232}$U concentration. The $W_0$ flow is the depleted uranium (DepU). The dilution is carried out as follows: enriched uranium produced from the RepU in the cascade, is diluted with a mixture that does not contain minor isotopes, achieving the desired content of the $^{235}$U isotope in the final LEU product.

In the Scheme 2 (figure 3) NatU, enriched to a higher level than necessary, is then mixed with RepU. This configuration avoids contamination of the separation equipment by $^{232}$U from RepU.

In Scheme 3 (figure 4) the reprocessed uranium (RepU) is pre-diluted with natural uranium (NatU) before enrichment.

For all variants (figures 2–4), the ratio between the consumption of the reprocessed and the diluent of natural origin is determined by the limit of the permissible concentration of $^{232}$U in the final product – low-enriched uranium. The negative reactivity of $^{236}$U compensation should also be taken into account. At the same time, the concentration of $^{235}$U should not be lower than that required for LEU with certain properties.

2.2. Statement of the problem

For the considered schemes, a series of computational experiments have been conducted. As a math model to calculate the enrichment procedure, we employed the R-cascade model also known as Matched Abundance Ratio Cascade [16, 17, 18]. Uranium hexafluoride gas is a working substance in the uranium enrichment performed by the gas centrifuge [19, 20]. The production of fresh LEU fuel from RepU and the additional $^{235}$U source was simulated for the following conditions:
Figure 3. Cascade with terminal dilution by RepU (Scheme 2).

Figure 4. Cascade with preliminary dilution (Scheme 3).

Table 1. The isotopic composition of spent fuel of the second recycle from VVER-1000.

| Mass number | 232 | 233 | 234 | 235 | 236 | 238 |
|-------------|-----|-----|-----|-----|-----|-----|
| Concentration, % | 6.62·10^{-7} | 1.19·10^{-6} | 3.28·10^{-4} | 1.43 | 0.9932 | 97.55 |

(i) Reprocessed uranium is derived from the light-water energy reactor. As an example, we will consider the isotopic composition of the reprocessed uranium extracted and recovered from the reactor of Russian design – VVER. The original isotopic composition of the RepU from the second recycle, presented in the table 1 [21].

(ii) Key components for which non-mixing in R-cascade model is set are: $^{235}$U and $^{238}$U.

(iii) Separation factor is equal to 1.2 for $^{235}$UF$_6$ to $^{238}$UF$_6$ [22].

(iv) The required concentration in the final product is 4.95%, which is typical for light-water reactors.

(v) Consumption of reprocessed uranium per unit of the final LEU product: 0.93 kg per 1 kg of LEU [23].

(vi) By default, the concentration of $^{235}$U in $W_0$ equal 0.1% [24].

(vii) $^{234}$U to $^{235}$U ratio should not exceed 0.02 [23].

(viii) The reactivity compensation ratio to neutralize the undesirable effect of neutron capture by isotope $^{236}$U is 0.29 and also corresponds to Russian light-water reactors [24].

(ix) The concentration of $^{234}$U in LEU is limited by 5·10^{-7}% [24].

With this representative formulation of the problem, we will check if the enrichment schemes based on an ordinary cascade could solve the uranium recycling problem.
3. Results and discussion

Let us start the analysis with the Scheme 1, when the RepU of the second recycle is enriched to a level exceeding the required concentration of $^{235}\text{U}$, and then diluted with NatU (figure 2).

The LEU product must simultaneously correspond to the required $^{235}\text{U}$ enrichment level, $^{232}\text{U}$ limitation and $^{236}\text{U}$ compensation condition. While the problem statement is associated with 3 concentrations and $\frac{\text{RepU}}{\text{P}}$ ratio, there are only two control parameters in such a problem: the $^{235}\text{U}$ output concentration and the proportion of mixed flows. Therefore, the possibility of obtaining a solution to the problem under such conditions is not defined. It is important to note that although the output concentration of $^{235}\text{U}$ is a control parameter, its change inevitably entails a change in the concentrations of $^{232,236}\text{U}$, thereby introducing additional uncertainty to the problem.

The curves on figures 5–8 reflect the dependencies of absolute values of residual errors $\delta_1, \delta_2$ in solving the system of equations for cascade from the proportion of natural uranium to the pre-enriched RepU. Here, $\delta_1 = \left[ C_{^{235}\text{U}}^P - \left( C_{^{235}\text{U}}^n + \text{RCC} \times C_{^{236}\text{U}}^P \right) \right]$ and $\delta_2 = \left[ C_{^{232}\text{U}}^P - 5 \times 10^{-7} \right] \times 10^5$.

![Figure 5. $^{235}\text{U}$ and $^{232}\text{U}$ discrepancies for $C_{^{235}\text{U}}^P = 15\%$](image)

![Figure 6. $^{235}\text{U}$ and $^{232}\text{U}$ discrepancies for $C_{^{235}\text{U}}^P = 30\%$](image)

![Figure 7. $^{235}\text{U}$ and $^{232}\text{U}$ discrepancies for $C_{^{235}\text{U}}^P = 50\%$](image)

![Figure 8. $^{235}\text{U}$ and $^{232}\text{U}$ discrepancies for $C_{^{235}\text{U}}^P = 65\%$](image)

According to its physical meaning, the value of $\delta_1$ is the absolute deviation of the concentration of $^{235}\text{U}$ isotope (expressed in mass fractions) in the final product (after mixing) from the required value, taking into account the compensation of $^{236}\text{U}$, and the value of $\delta_2$ is the difference between the actual concentration of $^{232}\text{U}$ in the final product and the required
value in compliance with the accepted limitation. In order to compare the indicated values in one figure, $\delta_2$ is multiplied by a specially selected numerical coefficient. $\delta_1$ and $\delta_2$ correspond to discrepancies in the solution of a system of nonlinear equations, which, in the case of a successful finding of a solution to the system of equations ($\delta_1 = 0$, $\delta_2 = 0$), will be equal to a value that does not exceed the maximum permissible calculation error in the numerical solution. Figures 5–8 are plotted for various values of the $^{235}\text{U}$ concentration in the pre-enriched RepU. For the successful solution of the system of nonlinear equations, both functions must equal zero ($\delta_1 = 0$, $\delta_2 = 0$) for the same value of the argument, which cannot be achieved, which is reflected in the given figures. Thus, the results obtained show the impossibility to use Scheme 1 (figure 2) with natural uranium as a diluent for the case of multiple uranium recycling.

To expand the possibility of solving this problem using a scheme based on an ordinary cascade, when the RepU is pre-enriched, it is necessary to replace the diluent with pre-enriched uranium that does not contain minor isotopes. In this case, it will be possible to find a solution when the conditions for $^{235}\text{U}$ and $^{232}\text{U}$ are simultaneously fulfilled (to achieve the equality of both residuals to zero). To investigate the range of parameters, where the cascade can operate and where it is most effective, two main quantities will be investigated below: the concentration of $^{235}\text{U}$ in the output flows $P_0$ and $W_0$. This will help illustrate, how the shares of NatU and RepU in the final LEU product change and how the separative work behaves.

Figure 9 illustrates that the Scheme 1 (figure 2) consumes the NatU to produce the necessary LEU product, at the level close to the ordinary cascade without RepU to produce the fresh LEU equivalent. For LEU from NatU the ratios would be 7.41, 8.55 and 11.3 for $C_{W_0}^{235}\text{U}=0.05\%$, 0.15% and 0.3% respectively. As we could see, the lower right corner of the plot 9, where the $^{235}\text{U}$ from RepU is raised to the highest levels (about 50% in mixture) and the feed is depleted greater, corresponds to the best configuration in terms of NatU savings. Having the higher level of $^{235}\text{U}$ extraction from RepU with lower $^{235}\text{U}$ concentration in $W_0$ helps us save the NatU, allowing for LEU diluent of lower $^{235}\text{U}$ level in figure 10 for Scheme 1 (figure 2), and having the deeper depleted tails ($C_{W_0}^{235}\text{U}=0.05\%$) allows to save some separative work as shown in figure 11 due to the more efficient extraction of $^{235}\text{U}$ from the RepU – a mixture in which the fraction of this target isotope is initially greater.

Figure 9. Natural uranium consumption per unit of LEU product for different concentrations of $^{235}\text{U}$ in the outputs of Scheme 1.

Figure 10. $^{235}\text{U}$ concentration in diluent required to produce fresh LEU for different concentrations of $^{235}\text{U}$ in the outputs of Scheme 1.

But, as figure 12 shows, there is no way to fulfill the conditions for returning a given proportion of RepU per unit of product. And the proportion of recycled material used per unit of product changes only slightly with an increase in the $^{235}\text{U}$ content in $P_0$. That is, the lengthening of
the enrichment part of the cascade does not lead to a significant increase in the RepU reclaim efficiency, therefore there is a little reason to increase the concentration of $^{235}$U in $P_0$ higher than 20%. The merging of the curves in figures 11 and 12, corresponding to different concentrations of $^{235}$U in the enriched RepU, is explained by the equivalence of the $^{235}$U masses in each of these streams, which reflects the equivalence of the contribution from the enriched RepU to the formation of the final product.

**Figure 11.** Separative work (SW) losses in comparison to ordinary cascade for natural uranium enrichment per unit of LEU product for different concentrations of $^{235}$U in the outputs of Scheme 1.

**Figure 12.** Reprocessed uranium consumption per unit of LEU product for different $^{235}$U concentrations in the Scheme 1 outputs.

It is possible to illustrate the costs of the separative work from the components of the cascade scheme using figure 13. To assess the impacts on separative work from different ordinary cascades in the scheme, as all separation devices in the R-cascade work in the same operating conditions, we could compare the proportions of centrifuges for preparing a diluent from natural uranium to centrifuges used for preliminary RepU enrichment. From that we could see that the NatU enrichment part requires more separative work and its share in total consumption decreases with a decrease in the $^{235}$U content in $W_0$, which is explained by higher level of $^{235}$U involvement from RepU.

**Figure 13.** The ratio of the centrifuges in the cascade producing diluent from natural uranium to the cascade enriching the RepU for different $^{235}$U concentrations in the Scheme 1 outputs.
Thus, the analysis of figures 9–12 shows the unsuitability of Scheme 1 (figure 2) with dilution of pre-enriched RepU with a mixture that does not contain minor isotopes to solve the problem under conditions of multiple recycling, since using such a scheme it is impossible to involve a given amount of RepU (0.93) in the production of a unit of commercial LEU. At the same time, an analysis of the graphs demonstrates that a decrease in the $^{235}\text{U}$ concentration in $W_0$ makes it possible to achieve the best implementation of the Scheme 1 shown in 10: to achieve savings in natural uranium per unit of product 9, to get by with a lower concentration of $^{235}\text{U}$ in the LEU diluent (figure 10), and also to save the separative work (figure 11), while the consumption of RepU per unit of product will be less by an insignificant amount (figure 12), not exceeding 1% in comparison with the cascade for enrichment of natural uranium. An analysis of the plots (figures 9, 10) demonstrates the possibility, with an increase in the level of enrichment of the RepU, to obtain greater savings in natural uranium due to the lower required concentration of $^{235}\text{U}$ in the LEU diluent. However, it should be noted that exceeding the $^{235}\text{U}$ concentration of the LEU level (20%) may be unacceptable in separation process, since such material falls into the category of highly enriched uranium (HEU), the production of which is limited [25].

Let us move on to the analysis of the Scheme 2 (figure 3), where pre-enriched natural uranium is mixed with reprocessed uranium returned to the fuel cycle. In such a cascade, it is possible to obtain a single solution for each combination of parameters. In this configuration, as in the case of using the Scheme 1 (figure 2), the consumption of RepU per unit of LEU product is insufficient (0.75), and the level of natural uranium enrichment in the cascade reaches 16% for different $^{235}\text{U}$ concentrations in the waste flow of this cascade. Consequently, such modifications of the three-flow cascade are not adequate for the task.

Another option for the implementation of the simplest modification of an ordinary cascade used to enrich natural uranium is ordinary mixing of natural uranium with RepU before feeding the resulting mixture to the cascade in proportion, determined from the limitation on even-numbered isotopes in the final LEU product. This Scheme 3 is shown in figure 4. The analysis shows (figure 14) that it is also impossible to achieve the required proportion of the consumption of RepU per unit of the final product (the solutions correspond to the intersections of curves with gray lines). The upper horizontal axis here and in the adjacent plot (figure 15) shows the proportion of the RepU in the feed isotopic mixture. Figure 15 shows that consumption of natural uranium per unit of product for the same set of found solutions could be even higher than in ordinary cascade for NatU enrichment.

Thus, the numerical experiments proved that we could not employ the cascades based on the ordinary three-flow cascade to enrich the degraded isotopic composition of reprocessed uranium. But what if we could assess the capability of the observed scheme to solve this task a priori? According to the balance equations 2 for material flows from which a special case was obtained by passing to the limit for the lightest isotope 3, which shows that to satisfy 1:1 RepU to LEU product requirement only when $^{232}\text{U}$ concentration in the initial RepU feed lower than the limitation of $^{232}\text{U}$ presence in the final product.

\[
F = P + W,
\]

\[
FC_i^F = PC_i^P + WC_i^W, \quad i = 1, 2, ..., m.
\]

, where $F$ is Feed, $P$ is Product, and $W$ is Waste flows.

Using this equation, the maximum possible share of the feed flow in $P$ containing $^{232}\text{U}$ can be calculated as the unknown variable of the equation, assuming that all the original $^{232}\text{U}$ will end up in the product 3:

\[
C_i^P \approx \frac{\text{RepU}}{P} C_i^{\text{RepU}}, \quad \text{where } i = 1 \text{ corresponds to } ^{232}\text{U}
\]
Figure 14. Reprocessed uranium consumption per unit of LEU product for varied concentration of $^{232}\text{U}$ in feed flow for different concentrations of $^{235}\text{U}$ in the waste flow of Scheme 3.

Figure 15. Natural uranium consumption per unit of LEU product for varied concentration of $^{232}\text{U}$ in feed flow for different concentrations of $^{235}\text{U}$ in the waste flow of Scheme 3.

\[ 5 \times 10^{-7} \% \approx \frac{\text{RepU}}{P} \times 6.622 \times 10^{-7} \% \Rightarrow \frac{\text{RepU}}{P} \approx 0.755 \quad (4) \]

The same limitation for \(\frac{\text{RepU}}{P}\) appears in figures 12 and 14, but 0.93 is required, from which it can be concluded that it is impossible to completely return (1:1) the RepU to the fuel cycle using schemes of the simplest modification of an ordinary cascade, because they not isolate the $^{232}\text{U}$ isotope, which should be withdrawn from the cascade at some point.

Let us calculate the limiting contribution of $^{235}\text{U}$ from the RepU, taking it as $X$:

\[ \frac{\text{RepU}}{P} \times \frac{C_{\text{RepU}}}{C_{4}} \Rightarrow X \approx 0.28, \text{ where } i = 4 \text{ corresponds to } ^{235}\text{U} \quad (5) \]

So, taking the $\text{RepU}$ as 0.93 and $P$ as 1, as in the problem statement, the limiting contribution of $^{235}\text{U}$ from RepU is limited to about 28%, which corresponds to the natural uranium savings. But in reality it would be even less due to the need to compensate for $^{236}\text{U}$ and the fact that some $^{235}\text{U}$ goes to the waste flow. As a result, as the $^{232}\text{U}$ in the RepU of the second cycle is already higher than the limitation, it is impossible to recycle the same amount of uranium multiple times with the ordinary-based cascades, either the RepU is preliminary enriched or used as a diluent of pre-enriched natural uranium. But there is a way out – to employ the cascades designed to detach the $^{232,234}\text{U}$ from $^{235}\text{U}$. Such schemes are based on two linked cascades, where in the first one, the $^{235}\text{U}$ is enriched with a simultaneous increase in the concentration of $^{232,234}\text{U}$ isotopes, but in the second cascade, the isotopic mixture is divided into light $^{232,233,234}\text{U}$ and heavy $^{235,236}\text{U}$ groups [26]. But this segregation of the lightest isotopes is associated with the accumulation of toxic waste that could be diluted by depleted uranium and reemployed. So, out of this paper’s scope, there are schemes that could succeed in the assigned task.

4. Conclusion
Considering the reprocessed uranium isotopic composition of the second recycle, the enrichment cascades based on an ordinary three-flow cascades could not be used to consume the whole amount of such material for fresh LEU production. We show that to recycle spent fuel multiply,
the degrading uranium isotope composition should be assumed. It shows up in the growing presence of $^{232,234,236}$U, which spoils the effect of their dilution by compositions without $^{232,236}$U (and with lower $^{234}$U concentration than in NatU). However, the outlined options could be used to re-enrich the reprocessed uranium on the first recycle at the required level of material involvement.

References
[1] Storing spent fuel until transport to reprocessing or disposal 2019 IAEA NF-T-3.3
[2] Uranium 2020: Resources Production and Demand 2021 NEA/IAEA
[3] Bogovalov S, Kislov V and Tronin I 2015 AIP Conf. Proc. 1648
[4] Bogovalov S, Borman V, Borisevich V, Tronin V and Tronin I 2017 AIP Conf. Proc. 1863
[5] De la Garza A, Garrett G A and Murphy J E 1961 Chem. Eng. Sci 15 188–209
[6] Abbas K, Cojazzi G, Mercurio G, Peerani P and Renda G 2013 ESARDA Bulletin
[7] Bernhardt H, Davis W and Shiflett C 1958 A/CONF.15/P/522
[8] Palkin V, Lubnin S and Tokmantsev V 2020 J. Phys. Conf. Ser 1696 012003
[9] Bogovalov S, Borman V, Vasilyev A, Tronin I and Tronin V 2020 J. Phys. Conf. Ser 1696 012012
[10] Sulaberidze A, Borisevich V and Quanxin X 2004 IX Int. conf. 78–85
[11] Palkin V and Maslyukov E 2020 NET 52 2867–2873
[12] Palkin V 2017 Atomic Energy 121 197–202
[13] Palkin V A 2013 At Energy 115 32–37
[14] Hida K, Kusuno S and Seino T 1986 Nucl. Technol. 75 148–159
[15] Gusev V 2020 J. Phys. Conf. Ser 1696 012009
[16] De la Garza A 1977 Nucl. Technology 32 176–185
[17] Sulaberidze G and Borisevich V 2001 Sep. Sc. and Tech. 36 1769–1817
[18] Sulaberidze G, Smirnov A, Borisevich V, Zeng S and Jiang D 2020 Sep. Sc. and Tech. 56 1060–1070
[19] Orlov A, Tsimbalyuk A and Malyugin R 2016 MATEC Web Conf. 72 01079
[20] Orlov nd Malyugin R 2015 AMR 1084 338–341
[21] Smirnov A, Gusev V, Sulaberidze G and Nevinitsa V 2020 At. Energy 128 223–231
[22] Smirnov A, Gusev V, Sulaberidze G, Nevinitsa V and Fomichenko P 2018 Bul. Nation. Res. Nuc. Univ. MEPhI 7 449–457 (in Russian)
[23] Smirnov A, Gusev V, Sulaberidze G and Nevinitsa V AIP Conf. Proc. 2101 020006
[24] Smirnov A, Sulaberidze G, Alekseev P, Dudnikov A, Nevinitsa V, Proselkov V and Chibinyaev A 2012 Phys. Atom. Nuclei 75 1616–1625
[25] Smirnov A, Gusev V, Volkov Y and Nevinitsa V AIP Conf. Proc. 2101 020007
[26] Smirnov A, Gusev V, Sulaberidze G, Nevinitsa V, Andrianova V and Blandinski V 2018 J. Phys. Conf. Ser 1099

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