Evaluating the effectiveness of dilution of the recovered uranium with depleted uranium and low-enriched uranium to obtain fuel for VVER reactors

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Abstract. The possibility of the recovered uranium enrichment in a cascade of gas centrifuges with three feed flows (depleted uranium, low-enriched uranium, recovered uranium) with simultaneous dilution of U-232,234,236 isotopes was shown. A series of numerical experiments were performed for different content of U-235 in low-enriched uranium. It has been demonstrated that the selected combination of diluents can simultaneously reduce the cost of separative work and the consumption of natural uranium, not only with respect to the previously used multi-flow cascade schemes, but also in comparison to the standard cascade for uranium enrichment.

1. Introduction

According to experts, despite the projected development and commissioning of fast reactors, almost inevitable imbalance between the estimated reserves of natural uranium and its consumption to fuel the current amount of reactors on thermal neutrons in the foreseeable future [1]. This demonstrates the necessity of using fissile materials extracted from spent nuclear fuel for supply such reactors. One of the possible materials is recovered uranium, the use of which will reduce the requirements for natural uranium and significantly reduce the amount of radioactive wastes, as compared with an open fuel cycle [2].

The recovered uranium can be used as raw material for production of low-enriched uranium in the cascades of gas centrifuges [2-7]. However, it is difficult to enrich such material due to the presence in its composition of isotopes $^{232}$U and $^{236}$U [2]. To the content of these isotopes in the low-enriched uranium (LEU) impose strict requirements related to the need to perform radiation safety conditions in the manufacture of fuel elements and save the neutron-physical characteristics of the nuclear fuel.

At the present, there is a number of ways to enrich recovered uranium in gas centrifuge cascades. Many of them are based on a simple cascade which has one feed flow, one product flow (commercial product) and one waste flow (depleted uranium). Such cascade may be used, for [8]:

• enrichment of pre-diluted with natural uranium recovered uranium;
• production of enriched recovered uranium followed by dilution with natural uranium or another diluent;
to enrich natural uranium to the content of $^{235}\text{U}$ slightly above the desired value for the fuel and consequent mixing of the product with the recovered uranium.

The main disadvantage of using such methods of recovered uranium enrichment are losing of the separation work due to the mixing of uranium with different contents of $^{235}\text{U}$ isotope.

Besides the mentioned above methods there other ways to enrich recovered uranium which are based on the use multi-flow separation cascades. Such cascades may have, for example, two feed flows (recovered uranium and natural uranium) [4] or an additional product flow [5]. The main advantage of using these cascades in comparison with three-flow cascades is minimization of separation work losses. However, a significant reduction of $^{232,234,236}\text{U}$ concentrations in low-enriched uranium is achieved, primarily due to dilution of recovered uranium by natural one. This fact leads to small savings of natural uranium (no more than 15%) [6].

More complex modification of multi-flow cascades to enrich the recovered uranium is a cascade with three feed flows, the first one is recovered uranium, the second one is depleted uranium, as the third feed it is possible to use either natural uranium or a small amount of low-enriched uranium [7, 9]. In the case of use of natural uranium and depleted uranium as diluents cascade with three feed flows provides a distinct advantage (over 50%) in the consumption of natural uranium, compared with the standard cascade for natural uranium enrichment. However, in this case, the loss of separation work can also be ~ 50% [7]. In case of using as the second diluent low-enriched uranium with $^{235}\text{U}$ content from 1.0 to 2.0% (in weight fractions) instead of natural uranium, it is possible to obtain the desired product with an economy both in separation work and consumption of natural uranium [9]. However, the question whether the use of such cascades effective or not in terms of production remains open.

This work is a continuation of the study [9]. The main purpose of the work is to evaluate the efficiency of the cascade with three feed flows to dilute the recovered uranium with low-enriched uranium and depleted uranium, as compared to the simple cascade for enrichment of natural uranium.

2. Mathematical model

As the object of study Matched Abundance Ratio Cascade (MARC) is considered. MARC is a model cascade in which relative concentrations of the selected pair of components are constant along the cascade length. This model is widely used for the analysis of the physical laws of mass transfer in cascades for separation of multicomponent isotope mixtures [10-12]. The schematic drawing of the cascade under consideration is presented on Fig. 1. The cascade has three feed flows ($F_1$, $F_2$, $F_3$) with concentrations $C_{i1}, C_{i2}, C_{i3}$, one product flow ($P$) and one waste flow ($W$) with concentrations $C^w_C, C^m_C$, where $i$ - the number of shared component mixture; $m$ - total number of components in the mixture. Hereinafter component concentration expressed in weight fractions. The $F_1$ is the flow of the waste uranium, $F_2$ is the flow of the recycled uranium and $F_3$ is the flow of the LEU-diluent. Cascade consists of $N$ stages connected symmetrically-countercurrent manner and numbered from the waste end of the cascade to the product one [11]. Flows $F_1$, $F_2$, $F_3$ entered stages $f_1$, $f_2$ and $f_3$, respectively. The mathematical model of such a cascade is described in [7].

The calculations were performed for the problem statement as follows: 1) given: concentrations $C^w_C, C^m_C$ (n - number of the target component - $^{235}\text{U}$), relations $F_2/F_3, F_2/F_1$; 2) cascade parameters to vary: $f_1, N$; 3) to be determined: $C^w_C, C^m_C (i \neq n), W/F_1, P/F_3$ and all internal parameters of the cascade. Such a problem could be solved by means of numerical method used in [7].

The stated problem is interesting from a practical point of view, because in this case is uniquely defined quality of the product that allows to compare the effectiveness of different ways of production of equivalent isotopic materials.
3. Results and discussion

Let us consider the enrichment of the recovered uranium with the following components concentrations: $^{233}\text{U} - 2.98 \times 10^{-7}\%$, $^{233}\text{U} - 5.81 \times 10^{-7}\%$, $^{234}\text{U} - 1.91 \times 10^{-2}\%$, $^{235}\text{U} - 0.901\%$, $^{236}\text{U} - 0.573\%$. This uranium mixture corresponds to spent fuel of Russian reactor VVER-1000 [9].

The MARC with no-mixing in the relative concentrations of the isotopes $^{235}\text{U}$ and $^{238}\text{U}$ is considered. The following cascade parameters were given: concentration of $^{235}\text{U}$ in the product was 4% (excluding additional enrichment in order to compensate the effect of $^{236}\text{U}$ presence), concentration of $^{233}\text{U}$ in the waste flow was 0.1%, the reactivity compensation coefficient was 0.29. The concentration of $^{232}\text{U}$ in the product was limited by value $2 \times 10^{-7}\%$ [2]. As diluents were considered the depleted uranium containing 0.25% $^{235}\text{U}$ and LEU with $^{235}\text{U}$ concentration varied from 1.0% to 2.0%. For each case the ratio of the natural uranium to the depleted one was varied. The results of calculation of cascade parameters were compared with the analogue values of the three-flow MARC to enrich natural uranium to the same concentrations of $^{235}\text{U}$ in the product and waste flows.

To compare the effectiveness of compared cascades as a criterion selected ratio of values $S$ which were calculated for the simple cascade and cascade with three feed flows by means of the following formula:

$$S = A_c \cdot Z + A_{F1} \cdot F_1 + A_{F2} \cdot F_2 + A_{F0} \cdot F_0,$$

where $Z$ - total number of separating elements (gas centrifuges) needed to enrich uranium at given concentrations of $^{235}\text{U}$ in outgoing flows, for the cascade with three feed flows this value also takes into account the number of separating elements needed for production of LEU-diluent; $A_c$ - coefficient that takes into account the costs associated with the work of separating elements; $F_0$ - natural uranium consumption for commercial LEU production; $A_{F1}$, $A_{F2}$, $A_{F0}$ - costs of the depleted, recovered and natural uranium, respectively.

This value largely determines the unit cost of production of the isotope product [13]. The first term in (1) is proportional to the cost of separation work, and the second one takes into account material cost to obtain the product. The calculations assumed that the average cost of natural uranium of about nine times more than the average cost of depleted uranium [14], and three times less than the cost of the uranium hexafluoride obtained from reprocessed uranium [15]. In the case of calculating the value of $S$ for the simple cascade, the value of $F_1$ and $F_2$ were set to zero.

Fig. 2 shows the ratio of $S$ parameter of the cascade with three feed flows and the simple cascade for cases with concentrations of $^{235}\text{U}$ in the LEU-diluent 1.1%, 1.5% and 2.0%. As can be seen from the curves on Fig. 2 unit cost of production of the commercial LEU decrease with increasing of concentration of $^{235}\text{U}$ in the LEU-diluent. Only at low concentration of $^{235}\text{U}$ in LEU-diluent unit costs will be higher than for the simple cascade. The greatest gain is obtained when the diluent has the highest concentration of $^{235}\text{U}$. 

![Figure 1. The schematic drawing of the cascade with three feed flows to enrich recycled uranium](image-url)
Figure 2. The dependence of the ratio for the $S$ parameter of the cascade with three feed flows ($S_{\text{reg}}$) and the simple cascade ($S_0$) versus the ratio between depleted uranium and LEU-diluent at various concentrations of $^{235}$U in it (curves 1, 2 and 3 correspond to concentrations of $^{235}$U 1, 1.1, 1.5 and 2.0% in LEU-diluent).

At the end, let us note that the use of cascade with three feed flows may allow to reduce the amount of storage of depleted uranium and spent fuel. For example, according to the data for 2009 in the USA alone amounts of storage of depleted uranium make up 708189 tons, and according to the work [1] to store the present amount the world's spent fuel it is necessary to have from 3 to 5 storages commensurate with the Yucca Mountain (USA). Obviously, when calculating the overall effect of the involvement of depleted and recovered uranium in the fuel cycle, one must consider reduced storage costs of these materials.

4. Conclusion
The scheme of the five-flow cascade (three feed flows, product and waste flows) of gas centrifuges to enrich recovered uranium with simultaneous dilution of its by low-enriched uranium and the depleted uranium is proposed. Based on the results of computational experiments the benefits of this cascade in comparison to the simple cascade in the value of the unit cost of production of the commercial LEU were shown.

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