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Research Article

Calculation of the cost of enriched uranium products in multi-stream cascades of enrichment process*

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Abstract

Modern uranium enrichment facilities can simultaneously use several raw materials as feed, including natural uranium, regenerated uranium obtained as a result of SNF reprocessing, or depleted uranium (all in the form of uranium hexafluoride). As the output of the separating cascade, several types of enriched uranium product with different levels of enrichment can be fabricated simultaneously. The paper proposes a methodology, absent in literature, for calculating the cost of each enriched uranium product in multi-stream separating cascades. The proposed methodology uses standard definitions of the isotopic value of feed and product stream and the Peierls-Dirac separation potential. Numerical calculations of the cost of enriched uranium products for three production problems are provided as examples of the methodology effectiveness: 1) involvement of depleted uranium hexafluoride (DUHF) in fabrication of enriched uranium product; 2) simultaneous fabrication of two enriched products; 3) use of depleted uranium to reduce the cost of the product with a higher enrichment level out of two (as applied, e.g., to advanced tolerant fuel). It has been shown that partial additions of DUHF as feed for a multi-product separating cascade make it possible to reduce the cost of a product with a higher level of enrichment; with the current market prices for natural uranium and separative work, there is a range of tails assays in which it is more profitable to enrich DUHF rather than natural uranium.

Keywords

Enriched uranium product cost, multi-stream enrichment process, separative work, effectiveness of depleted uranium involvement in enrichment process

Introduction

Modern facilities for separation of uranium isotopes are capable to use simultaneously more than one raw material as the separating cascade feed, including not only natural uranium but also regenerated uranium obtained as the result of SNF processing, or depleted (waste) uranium (all in the form of uranium hexafluoride). The separating cascade output may simultaneously include several types of enriched uranium product with different enrichment levels. While the cash value of raw materials is normally known (from market data or contract conditions), no calculation procedures to determine the cost of each of the enriched products could be found in available publications. Some publications deal with the topical problem of optimizing multi-stream cascades to clean regenerated uranium of ^{232}U, ^{234}U and ^{236}U isotopes which accumulate in the process of recirculating repeatedly regenerated ura-

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nium when using, e.g., REMIX fuel (Dekusar et al. 2013, Smirnov and Sulaberidze 2014, Palkin and Maslyukov 2019, Kovalev et al. 2020, Palkin et al. 2021). Issues involved in the economic efficiency of engaging depleted uranium hexafluoride (DUHF) in enrichment facilities and regenerated uranium and plutonium in fabrication of REMIX fuel are discussed in (Pavlov et al. 2019, Matveyenko et al. 2021, Ulyanin and Kharitonov 2021). These studies do not however consider the enrichment of DUHF and regenerated uranium with fabrication of the only product, an equivalent of natural uranium or enriched uranium product respectively.

The purpose of the study is therefore to propose a methodology for calculating the cost of each enriched uranium product in multi-stream separating cascades.

One-product cascade economics

Fig. 1A shows a standard flow diagram for enrichment of natural uranium with weight $F(c)$ with the only product with mass $P(x)$ and enrichment x with tails mass $D(y)$ and tails assay y (concentration of ^{235}U in uranium tails). The cumulative costs, З, that define the enriched product price (cost price), $C_x = \text{З}/P$, include the raw material payment at price Ц_F, separative work, R, at price Ц_R, and recycling of uranium tails at price Ц_D according to a well-known formula (Sinev 1987, Gordeyev 2001, Borisevich et al. 2005, Kharitonov 2014, Pavlov et al. 2019)

$$\text{З} = F\text{Ц}_F + R\text{Ц}_R + D\text{Ц}_D, \qquad (1)$$

including the three above types of costs. We shall note that the cost of separative work, as shown in (Rothwell 2009), depends on the plant's capacity because of the scale factor. For the purpose of this study, however, all prices in formula (1) are treated as given.

The generally accepted definition of separative work is expressed as the difference between the isotopic value of products (enriched uranium and tails) and the raw material (natural uranium) in the form shown in (Sinev 1987, Gordeyev 2001, Borisevich et al. 2005, Kharitonov 2014)

$$R = P(x)V(x) + D(y)V(y) - F(c)V(c), \qquad (2)$$

where $V(z) = (1 - 2z)\ln[(1 - z)/z]$ is the Peierls-Dirac separation potential ($z = x$, y or c).

Isotopic value is the product of the stream weight by the stream separation potential (e.g., the value of the enriched product is $P(x)V(x)$). The relationship among streams F, P and D follows from the balance of the masses as coefficients of the natural uranium consumption per the product unit, (F/P), and the mass formation per the product unit, (D/P)

$$F/P = (x - y)/(c - y);\; D/P = F/P - 1 = (x - c)/(c - y). \qquad (3)$$

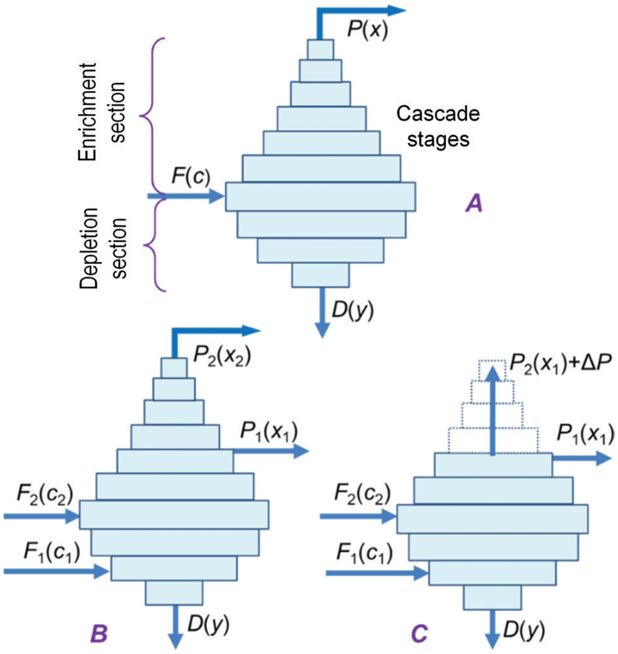

Figure 1. Flow diagram of separating cascades: **A.** Traditional cascade with one feed stream, $F(c)$, of natural uranium and one stream of enriched uranium product, $P(x)$, with a waste stream of $D(y)$; **B.** Cascade with two feed streams and two streams of enriched uranium; **C.** A part of cascade B with the same two feed streams as in Fig. B but with one cascade outlet (intermediate) stream of product, $P_{x1} = P_1(x_1) + P_2(x_1) + \Delta P$, with enrichment x_1.

Substituting (3) in (2) leads to the classical definition of specific separative work (also referred to as separative work standard)

$$R/P = V(x) + V(y)(x - c)/(c - y) - V(c)(x - y)/(c - y). \qquad (4)$$

Substituting expressions (2) through (4) in formula (1) leads to the traditional definition of costs, З, for the enrichment of natural uranium and the enriched uranium product cost, C_x(\$/kg),:

$$C_x = \text{З}/P = \text{Ц}_F(x - y)/(c - y) + \text{Ц}_R[V(x) + V(y)(x - c)/(c - y) - V(c)(x - y)/(c - y)] + \text{Ц}_D(x - c)/(c - y). \qquad (5)$$

The only parameter, using which the product cost can be handled with the given product enrichment, x, and determined prices for the raw material (natural uranium with a concentration of c =0.711%), separative work and tails recycling, is tails assay y (concentration of ^{235}U in uranium tails). As shown in (Kharitonov 2014), the optimum tails assay, which leads to the minimum cost of enriched uranium, depends only on the ratio of prices, $(\text{Ц}_F + \text{Ц}_D)/\text{Ц}_R$, and does not depend on the product enrichment. Thus, according to the 2020 data, the annual average spot quotes amounted to 75 \$/kgU for natural concentrated uranium dioxide, 21 \$/kgU (that is, Ц_F = 96 \$/kgU) for conversion services, and Ц_R = 49 \$/kgU for separative work (JSC Atomenergoprom. 2020 Annual Report). Assuming that Ц_D = 7 \$/kgU, we get (Ц_F +

$Ц_D)/Ц_R = 2.1$ and the optimum tails assay of $y_0 = 0.154\%$ which fits the minimum cost of $C_x = 1359$ \$/kgU for uranium product enriched to $x = 4.95\%$. The costs of natural uranium (in the form of hexafluoride) account for 61% in this value, and those of separative work and tails recycling make 35% and 4% respectively.

Multi-product cascade economics

Fig. 1B shows a flow diagram of multi-product enrichment with several streams of the cascade feed and product removal. Two feed streams, $F_1(c_1)$ and $F_2(c_2)$, and two enriched product removals, $P_1(x_1)$ and $P_2(x_2)$, were considered for illustration and simplification of records, with the concentration of ^{235}U in feed streams meeting conditions $y < c_1 < c_2 \leq c = 0.711\%$, and the product enrichment meeting $c < x_1 < x_2$. The expressions presented below can be easily generalized with respect to any number of feed and removal streams.

By generalizing the approach in (Gordeyev 2001) to the analysis of enrichment for a combination of raw materials, it is possible to show, for a random number of raw material and product streams, that the calculation of separative work and the cumulative product cost is reduced to 'one-product' model A with the only difference that weight-average values are used for the product and raw material streams respectively instead of concentrations x and c, separation potentials $V(x)$ and $V(c)$, and raw material prices $Ц_F$:

$$\langle x\rangle = (x_1P_1 + x_2P_2)/P;\ \langle c\rangle = (c_1F_1 + c_2F_2)/F;\\ P = P_1 + P_2;\ F = F_1 + F_2; \tag{6}$$

$$\langle V(x)\rangle = [V(x_1)P_1 + V(x_2)P_2]/P;\\ \langle V(c)\rangle = [V(c_1)F_1 + V(c_2)F_2]/F; \tag{7}$$

$$Ц_F\rangle = [F_1Ц_{F1} + F_2Ц_{F2}]/F = fЦ_{F1} + (1-f)Ц_{F2}. \tag{8}$$

Here, P and F are the cumulative masses of the enriched product and feed streams respectively; and $f = F_1/F$ is the share of the cascade feed with a smaller concentration of ^{235}U. Expressions (6) and (7) follow unambiguously from the classical definition of separative work with regard for the isotopic value of all feed and removal streams looking as follows for flow diagram B:

$$R_B = P_1V(x_1) + P_2V(x_2) + D(y)V(y) - F_1V(c_1) - F_2V(c_2). \tag{9}$$

For a multi-product cascade, as a result, we obtain analogs of expressions (4) and (5) for specific separative work and unit costs as follows

$$R_B/P = \langle V(x)\rangle + \langle V(y)\rangle(\langle x\rangle - \langle c\rangle)/(\langle c\rangle - y) - \langle V(c)\rangle\\ (\langle x\rangle - y)/(\langle c\rangle - y) \equiv V_B; \tag{10}$$

$$З_B/P = \langle Ц_F\rangle(\langle x\rangle - y)/(\langle c\rangle - y) + Ц_RV_B + Ц_D\\ (\langle x\rangle - \langle c\rangle)/(\langle c\rangle - y). \tag{11}$$

Value V_B in expression (10) is the specific separative work or the separative work rate for a multi-product separating cascade. It follows from expression (10) and (11) that, with the given feed and product removal parameters, there is an optimum tails assay, y_0, with which the enriched product fabrication costs are as small as possible, while, as in the previous case (flow diagram A), value y_0 depends only on the price ratio. In particular, if the cascade feed consists of natural uranium ($c_2 = c = 0.711\%$) and depleted uranium hexafluoride (DUHF) streams with a zero value ($Ц_{F1} = 0$), which have equal masses, then we get for the above market prices that ($Ц_{F2} \equiv Ц_F$, $F_2/F = F_1/F = 1/2$)

$$\langle Ц_F\rangle = Ц_F/2;\ (\langle Ц_F\rangle + Ц_D)/Ц_R = 1.12 \text{ and } y_0 = 0.216\%.$$

Expression (11), with the given enriched product weight, P, defines the *cumulative separation costs* for purchasing two types of raw materials for the cascade feed (the first term in the second member) and for separative work with two enriched uranium product removals (the second term) taking into account the tails recycling costs (the final term). The costs for each raw material type in formula (11) have been determined, while the isotope separative work costs for each enriched product, as well as the raw material value contribution to the cost of each enriched product have not been determined, this making it impossible to estimate the cost of each enriched product. We shall use flow diagram C to solve this problem.

Distribution of costs for manufacturing of enriched products and estimation of their cost price

The theory of separating cascades (Sinev 1987, Borisevich et al. 2005) supposes that the cascade separative work is computed as the total of separative works at each cascade stage. We shall therefore estimate initially the separative work prior to the removal of the first product with a smaller enrichment, $x_1 < x_2$ (Fig. 1C). The separating cascade in the figure is a part of the stage shown in Fig. 1B. At the inlet in the stage for the removal of a product with enrichment x_1, the enriched stream mass exceeds the mass of finished products, $P = P_1 + P_2$, by certain value ΔP in accordance with the enriched mass dynamics in the separating cascade's enrichment section (with regard for the depleted mass reverse stream):

$$F/(P + \Delta P) = (x_1 - y)/(\langle c\rangle - y) \text{ or}\\ \Delta P/P = \beta_2(x_2 - x_1)/(x_1 - y). \tag{12}$$

In the above expression, $\beta_2 = P_2/P$ demotes a mass fraction of a product with a higher enrichment level in the separating cascade's product portfolio and takes into account that, according to (10),

$$F/P = (\langle x\rangle - y)/(\langle c\rangle - y) \text{ и } \langle x\rangle - x_1 = \beta_2(x_2 - x_1).$$

It follows from (12) that $\Delta P = 0$ with $x_1 = x_2$ and $\beta_2 = 0$. If $\beta_2 = 1$, then, simultaneously, $x_1 = x_2$. We obtain the separative work for flow diagram C, by analogy with standardly derived formulas (4) and (10), as follows

$$R_C/(P + \Delta P) = V(x_1) + V(y)(x_1 - \langle c\rangle)/(\langle c\rangle - y) - \langle V(c)\rangle(x_1 - y)/(\langle c\rangle - y) \equiv V_C, \quad (13)$$

where RC is the separative work upstream of the enriched uranium first removal stage in flow diagram C; and V_C is specific separative work (or the separative work rate) in flow diagram C.

Difference $\Delta R = R_B - R_C$ between separative work (10) for flow diagram B and separative work (13) for flow diagram C leads to the amount of separative work per the *increase of the enrichment* of uranium mass $P_2 + \Delta P$ from x_1 to x_2 to obtain the second product of mass P_2. It remains only to distribute, among each commercial product, separative work, R_C, as well as the feedstocks in flow diagram B defined by the first term in formula (11), and the tails recycling costs defined by the final term in formula (11). We shall denote the total of the feedstock and tails recycling costs as:

$$З_{BFD} = P[\langle Ц_F\rangle(\langle x\rangle - y)/(\langle c\rangle - y) + Ц_D(\langle x\rangle - \langle c\rangle)/(\langle c\rangle - y)]. \quad (14)$$

As part of the traditional approach to the separative work calculation under consideration, it appears logical to distribute values $З_{BDF}$ and R_C in proportion to the mass fraction of each enriched product. As the result, the cumulative costs for each enriched product are determined as:

$$З_1 = \beta_1(З_{BDF} + R_C Ц_R);\ З_2 = \beta_2(З_{BDF} + R_C Ц_R) + \Delta R_C Ц_R, \quad (15)$$

where $b_1 = P_1/P$ and $b_2 = 1 - b_1 = P_2/P$ are relative mass fractions of removed enriched products. Expression (15) satisfies the condition $З_1 + З_2 = З_B$. As a result, the cost of each enriched product is determined

$$C_{x1} = З_1/P_1 = (З_{BDF} + R_C Ц_R)/P = \langle Ц_F\rangle(\langle x\rangle - y)/(\langle c\rangle - y) + Ц_D(\langle x\rangle - \langle c\rangle)/(\langle c\rangle - y) + V_C Ц_R(\langle x\rangle - y)/(x_1 - y); \quad (16)$$

$$C_{x2} = З_2/P_2 = C_{x1} + Ц_R \Delta R/P_2. \quad (17)$$

As can be seen from (17), the cost of a product with a large enrichment exceeds the cost of a product with a smaller enrichment by

$$Ц_R\Delta R/P_2 = Ц_R[PV_B - V_C(P + \Delta P)]/P_2 = Ц_R[V(x_2) - V(x_1)(x_2 - y)/(x_1 - y) + V(y)(x_2 - x_1)/(x_1 - y)]. \quad (18)$$

Hence it follows that $\Delta R = 0$ with $x_1 = x_2$. Therefore, the cost of each enriched product has been determined. The obtained results can be used to solve a number of manufacturing tasks. Presented below as examples are numerical calculations of the enriched product cost for the three following problems: involvement of depleted uranium hexafluoride (DUHF) in fabrication of enriched uranium product, 2) simultaneous fabrication of two enriched products, and 3) involvement of DUHF for reducing the value of a product with a higher enrichment level out of two (as applied to advanced tolerant fuel).

Estimation of the enriched uranium product value in the cascade feed with natural uranium and DUHF

By now, there is some 2 million tons (Mt) of uranium hexafluoride with a ^{235}U concentration in a range of 0.1 to 0.4 wt.% (in terms of uranium metal) accumulated worldwide (Peter Diehl 2004, Pavlov et al. 2019, Dirk Bannink 2020). Different concentrations of ^{235}U in DUHF are explained by the process conditions and economic considerations associated with the enrichment facility loading and the ratio of prices for the uranium isotope separative work and for natural uranium. In detail, the flow diagrams for the DUHF involvement in fabrication of enriched uranium product or an equivalent of natural uranium are discussed in (Pavlov et al. 2019). We shall estimate here only the dependence of the enriched uranium product value, C_x ($x_2 \equiv x = 4.95\%$), on the fraction of DUHF in the cascade feed ($f = F_1/F$) and the concentration of ^{235}U in the DUHF feed (c_1) and in the cascade's uranium tails (y). The fraction of the feed DUHF (from the external customer) is variable in a range of $f = 0$ (flow diagram A) to $f = 1$. In the latter case, when the cascade feed consists of only DUHF, the enriched uranium value is determined by expression (5) with c substituted for c_1 and $Ц_F$ for $Ц_{F1}$.

The concentration of ^{235}U in DUHF is smaller than in natural uranium, so more separative work, than in the event of only natural uranium enrichment, will be required for a greater output of the given amount of enriched uranium. But the cost of DUHF ($Ц_{F1}$) can be much below the natural uranium price ($Ц_{F2}$), so one can hope that the economic effect is positive.

It follows from Fig. 2, which presents the direct cost calculation result for the EUP obtained in the DUHF and natural uranium enrichment, there is a range of the separating cascade's tails assay in which it is more profitable to enrich DUHF rather than natural uranium, with the existing market prices for natural uranium and separative work unit ($Ц_{F2}/Ц_R > 1$). The higher is the price of natural uranium, as compared with the price of a separative work unit (the larger is the $Ц_{F2}/Ц_R$ ratio), the more profitable it is to enrich DUHF. The EUP cost is much affected by the DUHF entry price (0 to 10 \$/kgU).

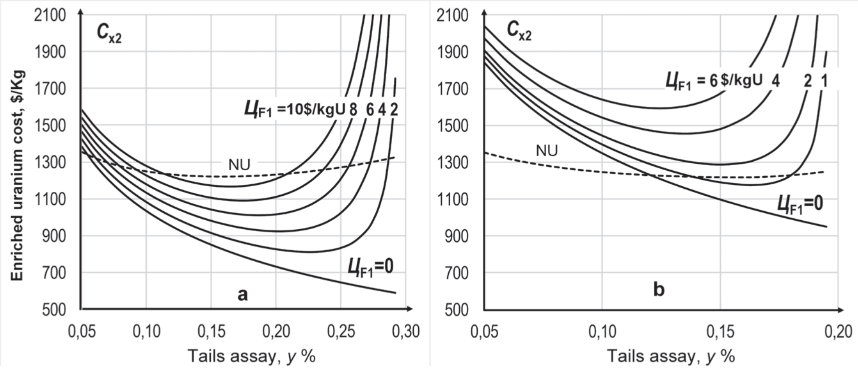

Figure 2. Cost of 4.95% enriched uranium product obtained from DUHF with a concentration of y_1=0.3% (a) and 0.2% (b), as a function of the secondary tails assay (y) and the DUHF cost (C_D= 0 to 10 $/kgU), with market quotes for natural uranium hexafluoride (C_F=90 $/kgU) and for separative work (C_R=45 $/SWU). The NU dashed line shows the cost of EUP from natural uranium.

In the limiting case of the DUHF zero price, it is more profitable to enrich DUHF rather than natural uranium practically across the tails assay range (up to 0.3% with the DUHF enrichment level of 0.3%) (Fig. 2a). The DUHF price increase to 10 $/kgU increases greatly the EUP cost, reduces the profit (per 1 kg of the EUP), and reduces the industrial tails assay range for the cost-effective enrichment of DUHF. With the concentration of ^{235}U in DUHF being below 0.3%, the DUHF profitability range decreases greatly (Fig. 2b).

With the given installed capacity of the separating cascade, the generated EUP mass (per separative work unit, P/R) increases with the ^{235}U concentration growth in the tails (Fig. 3), the cascade feed in the form of DUHF reducing by nearly a half the product output per separative work unit as compared with the cascade's feed with natural uranium.

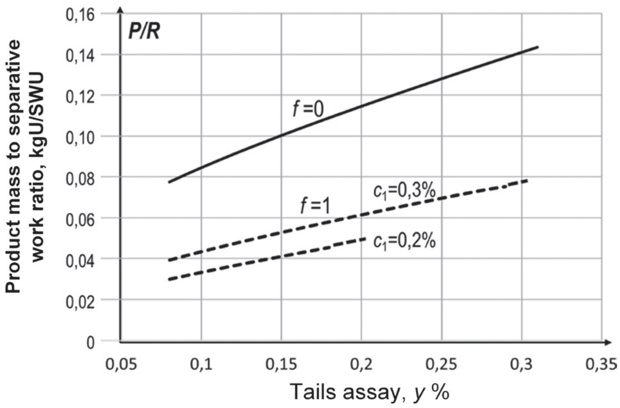

Figure 3. Ratio, P/R, of the enriched product mass to the separative work costs (in kgU/SWU) with enrichment of up to x=4.95% for natural uranium (f=0) or depleted uranium hexafluoride (DUHF, f=1), the content of uranium-235 in DUHF being 0.3% and 0.2% depending on the separative cascade tails assay (y = 0.08 – 0.31%).

Estimation of cost for two enriched uranium products with the cascade natural uranium feed

Let us estimate the dependence of the cost of each of the products with enrichments x_1 = 2.5% and x_2 = 4.95% (e.g., for RBMK and VVER reactors) on the mass fraction, $\beta_1=P_1/P$, of a low enriched product and the tails assay, y = 0.05 – 0.35%. The fraction of the low enriched product is variable in a range of β_1 = 0 (flow diagram A, only EUP with an enrichment of x_2 = 4.95% is fabricated) to β_1=1 (flow diagram A, only EUP with an enrichment of x_1 = 2.5% is produced). In the latter case, when the cascade product consists of only low enriched uranium (x_1 = 2.5%), its value is determined by expression (5) with x changed for x_1. It follows from Fig. 4 that the price of the cascade products with two product removals are between the two boundaries: the upper boundary is the cost of a monoproduct with a higher enrichment level (x_2), and the lower boundary is the cost of a monoproduct with a lower enrichment level (x_1). That is, two-product manufacturing makes a more expensive product cheaper and, vice versa, makes a cheaper product more expensive.

Method to reduce the low enriched product cost through the use of DUHF in the cascade feed

It is possible to check in this section to which extent the cost of a high enriched product can be reduced (e.g., with x_2 = 7% as for advanced tolerant fuel with a 24-month fuel cycle (State-of-the-Art Report, Karpyuk et al. 2021a, b, Semenov and Kharitonov 2021)) if DUHF is used as the feed along with natural uranium. The thing is that a reduction in the average weighted enrichment of feed streams leads to a growth in separative work and respective costs, but, since DUHF may have a zero value, there may be a gain in the cumulative costs and the product cost can be reduced as the result. We shall consider an option with two products with enrichments x_2 = 7% (for tolerant fuel) and x_1 = 4.95% (for conventional fuel), depending on the fraction of highly enriched product, $\beta_2=P_2/P$, and on the fraction of DUHF in the cascade feed, $f=F_1/F$, fabricated simultaneously in a separating cascade. The value calculation results for both products are presented in Table 1 and in Fig. 5.

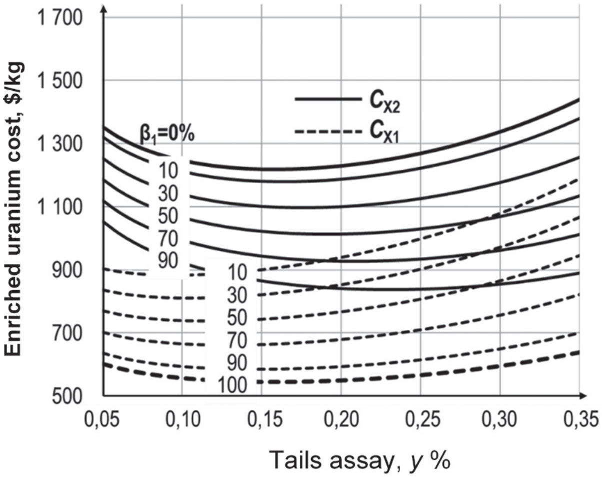

Figure 4. Cost of enriched uranium products with x_1=2.5% and x_2=4.95% as a function of the low enriched product's mass fraction (β_1 = 0 – 100%) and the two-product separating cascade's tails assay (y = 0.05 – 0.35%) with natural uranium feed.

As it follows from the table, the cost of an enriched uranium product in a one-product cascade with only natural uranium feed (f = 0) amounts to 1219 \$/kgU (x_1 = 4.95%) and 1793 \$/kgU (x_2 = 7%) with the same tails assay, y=0.15%. The cost of the same products with the one-product cascade feed of only DUHF (f = 1) with the ^{235}U isotope concentration of c_1 = 0.3% and of zero value decreases respectively to 850 and 1267 \$/kgU (by about a factor of 1.42). Simultaneous manufacturing of products with different enrichments in a two-product separating cascade with only natural uranium feed leads to a reduction in the price for a product enriched to a higher level (from 1267 to 978 \$/kgU) and an increase in the price of a product enriched to a lower level (from 850 to 923 \$/kgU). And the price of a 4.95% enriched product remains much below 1219 \$/kgU which corresponds to an only natural uranium cascade feed. The obtained results show that it is possible to reduce considerably the cost of enriched uranium products in a multi-product separating cascade when using depleted uranium hexafluoride as the cascade feed.

Table 1. Cost price of enriched uranium products in a two-product separating cascade with x_1 = 4.95% and x_2 = 7% depending on the fraction of a high enriched product ($\beta_2 = P_2/P$ =0 – 1) and the fraction of DUHF with a concentration of c_1 = 0.3% in the cascade feed (f = 0 – 1). Initial prices: $Ц_{F1} = Ц_D$ =0, $Ц_{F2}$ = 90 \$/kgU, $Ц_R$ = 45 \$/SWU. Tails assay: y = 0.15%

Cost \$/kgU	Natural uranium feed f = 0, <c> = 0.711%				DUHF feed f = 1, <c> = 0.3 %			
	β_2=0	β_2=0.2	β_2=0.8	β_2=1	β_2=0	β_2=0.2	β_2=0.8	β_2=1
$C_{x1}(x_1$=4,95%)	**1219**	1323	1635	–	**850**	923	1141	–
$C_{x2}(x_2$=7%)	–	1377	1689	**1793**	–	978	1195	**1267**

The calculation results presented in Fig. 5 show that the cost of both products does not practically depend on the separating stage tails assay (lower curves) with the given sufficiently high enrichment of products and with the cascade feed of only DUHF (f = 100%) of zero value. A reduction in the fraction of DUHF in the cascade feed is accompanied by an increase in the tails assay effects on the cost of both products.

A decrease in the fraction of DUHF in the cascade feed leads to an increase in the cost of both products this increase being the greater the greater is the tails assay. An increase in the fraction of a product with a higher enrichment level (up to 80%) leads to a growth in the cost of both products (Fig. 5b). The change in the composition (fractions) of products and the composition (fractions) of the separating cascade feed is accompanied by a major change in the product output (per separation work unit) and the feed demand (per product unit) as shown in Table 2.

Conclusions

A novel methodology is presented for calculating the distribution of costs for each enriched product and, accordingly, the cost of each product in a multi-stream separating cascade. The methodology uses the standard definition of separative work and the Peierls and Dirac separation potential.

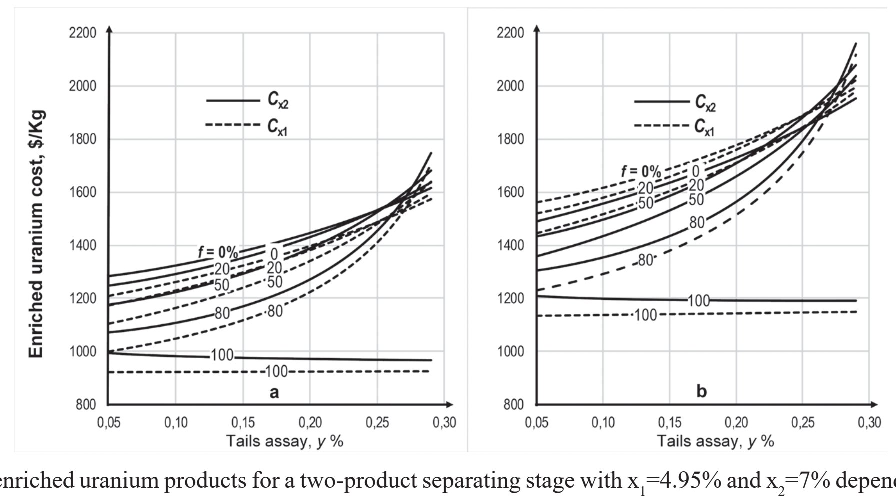

Figure 5. Cost of enriched uranium products for a two-product separating stage with x_1=4.95% and x_2=7% depending on the fraction of DUHF with a concentration of c_1=0.3% in the cascade feed (f = 0 – 1) and the fraction of high enriched product ($\beta_2 = P_2/P$), equal to 0.2 (a) and 0.8 (b), with a tails assay of y = 0.15%. Thicker lines match the limiting values of f = 0 and f = 100%. Initial prices: $ЦF_1$ = ЦD = 0, $ЦF_2$ = 90 \$/kgU, ЦR = 45 \$/SWU.

Table 2. Effects of the DUFH fraction (f) in the feed for a two-product separating cascade and the fraction (β_2) of a high enriched product (x_2 = 7%) on the cumulative output of enriched uranium products (*P*, tons) per 1 million separative work units (*R*, mln SWU) and on the feed demand (*F*) per product unit (*P*) with x_1 = 4.95% and a tails assay of y = 0.15%

f	β_2=0		β_2=0,2		β_2=0,8		β_2=1	
	P/R t/mln SWU	*F/P*	*P/R* t/mln SWU	*F/P*	*P/R* t/mln SWU	*F/P*	*P/R* t/mln SWU	*F/P*
0.0	100	7.6	90	8.3	70	10.5	65	11.2
0.2	95	9.0	86	9.9	66	12.5	62	13.3
0.5	84	12.5	76	13.6	59	17.1	55	18.3
0.8	69	19.7	62	21.4	49	26.7	45	28.5
1.0	53	31.0	48	33.7	38	41.9	35	44.7

The results obtained based on the proposed methodology are presented for numerical calculations of the enriched uranium product cost for three fabrication problems: 1) involvement of depleted uranium hexafluoride (DUHF) in fabrication of enriched uranium product, 2) simultaneous fabrication of two enriched products, and 3) use of DUHF for reducing the cost of the product with a higher enrichment out of the two (as applied to advanced tolerant fuel).

It has been shown that manufacturing of two products (as compared with manufacturing of one product) makes a more expensive product cheaper and, vice versa, makes a cheaper product more expensive. Additions of DUHF as a feed for a multi-product separating cascade make it possible to reduce the cost of a product with a higher level of enrichment and to increase to a certain extent the cost of a product with a lower level of enrichment. It has also been shown that the existing market prices for natural uranium (in the form of uranium hexafluoride) and separative work lead to a separating cascade tails assay range in which it is more profitable to enrich DUHF rather than natural uranium.

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