Re-enrichment of depleted uranium tails in Gaseous Diffusion Plants

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Abstract

Large amounts of depleted uranium tails are stored in so-called uranium hexafluoride cylinder yards next to the enrichment plants in various countries, waiting for a decision on any future use or final disposal. Now, in the times of steep jumps of the uranium price, the question is raised, whether these tails can be profitably processed to recover some of the residual U-235 contained. So far, such re-enrichment has been performed in very special circumstances only, and in particular only in energy-efficient gas centrifuge plants. Recently, however, several proposals have been made to use also energy-intensive gaseous diffusion plants (GDP) for re-enrichment. This paper analyses the technical and economical viability of these proposals, and their environmental impacts, such as waste balance, consumption of electricity, and associated CO_2 emission.

1. Introduction

The uranium enrichment process generates not only a product stream of uranium enriched in the isotope U-235, but also a much larger waste stream of depleted uranium tails. The tails assay, that is the residual concentration of U-235 in the depleted uranium, can be selected according to economic needs. With lower tails assays, more enriched uranium (LEU product) can be produced from a given amount of natural uranium feed, at the expense of excess separation work. The required increase in separation work is disproportionate to the excess product obtained, though, as shown in Fig. 1: compared to a 0.3% tails assay, a 0.2% tails assay leads to a 21% product increase, requiring 50% more enrichment work; and at 0.1% tails assay, a 40% product increase is obtained, requiring 140% more enrichment work.

The tails assay thus becomes an object of economic optimization: based on market prices for enrichment work and for natural uranium, the total cost can be minimized by selecting an appropriate tails assay.
Fig. 2 shows the cost of 1 t of uranium product (enriched to 3.6 wt-% U-235) for the cost situation of Dec. 25, 2000, when the uranium spot price was at a historic low of US$ 7.10 / lb U_3O_8: the total cost shows a minimum for a tails assay of approx. 0.37%.
Fig. 3 shows the same for the cost situation of June 4, 2007, when the uranium spot price was at a historic high of US$ 135 / lb U_3O_8 (the costs for conversion and enrichment had increased, as well, but at a lower rate). The total cost is much higher and it now shows a minimum for a tails assay of approx. 0.13%.

Fig. 1:

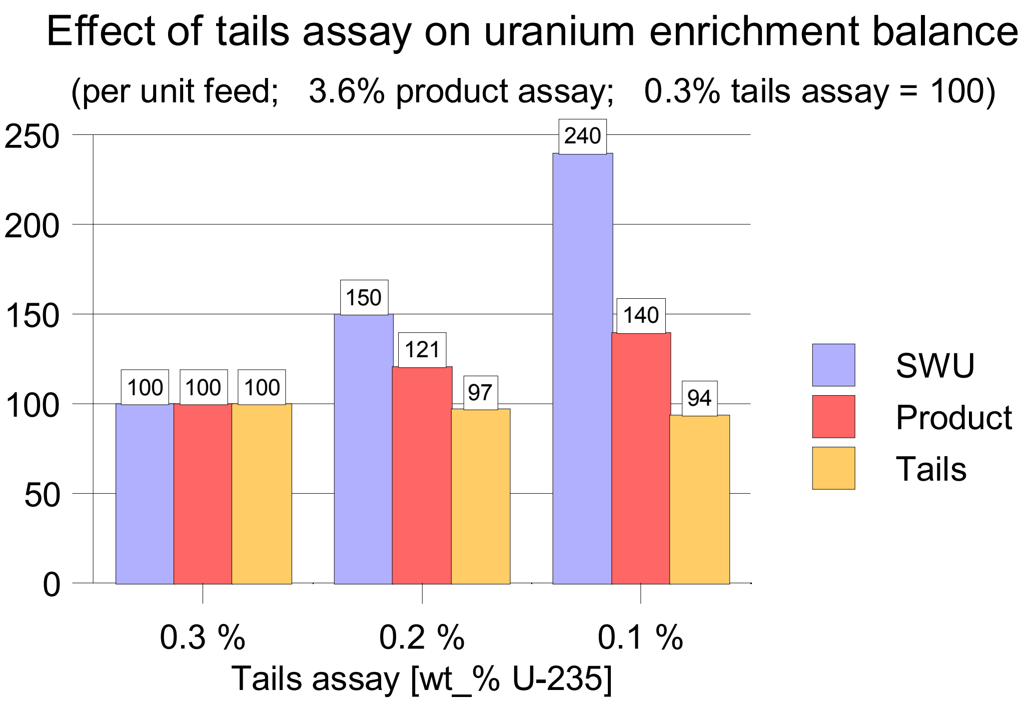


Fig. 2: Stacked cost at prices of Dec. 25, 2000

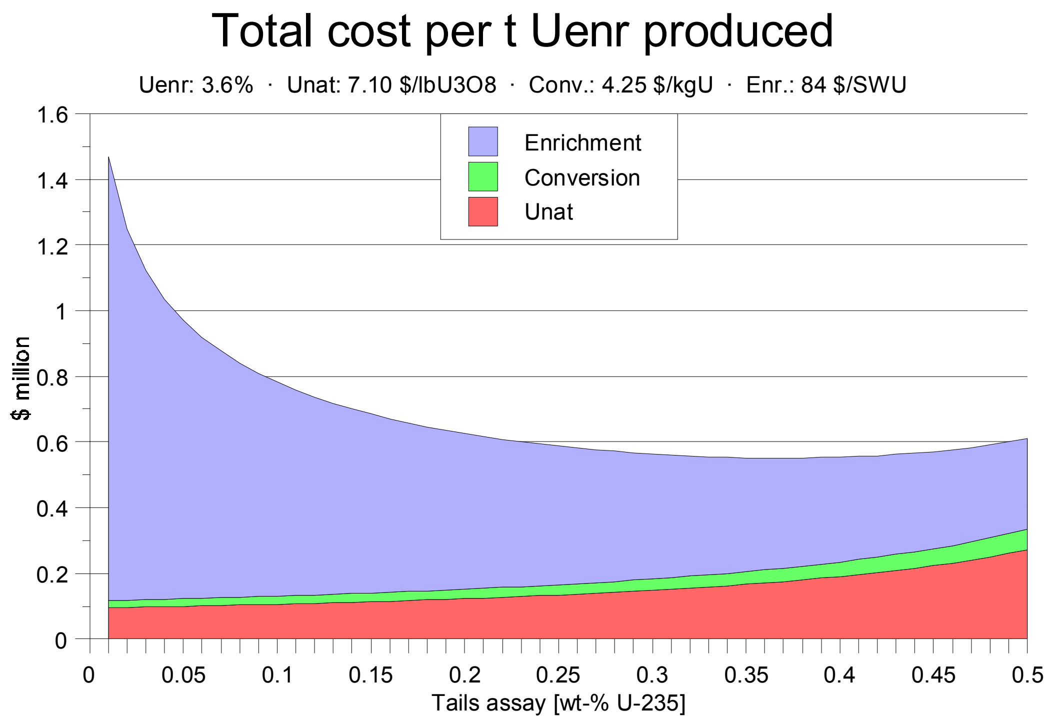
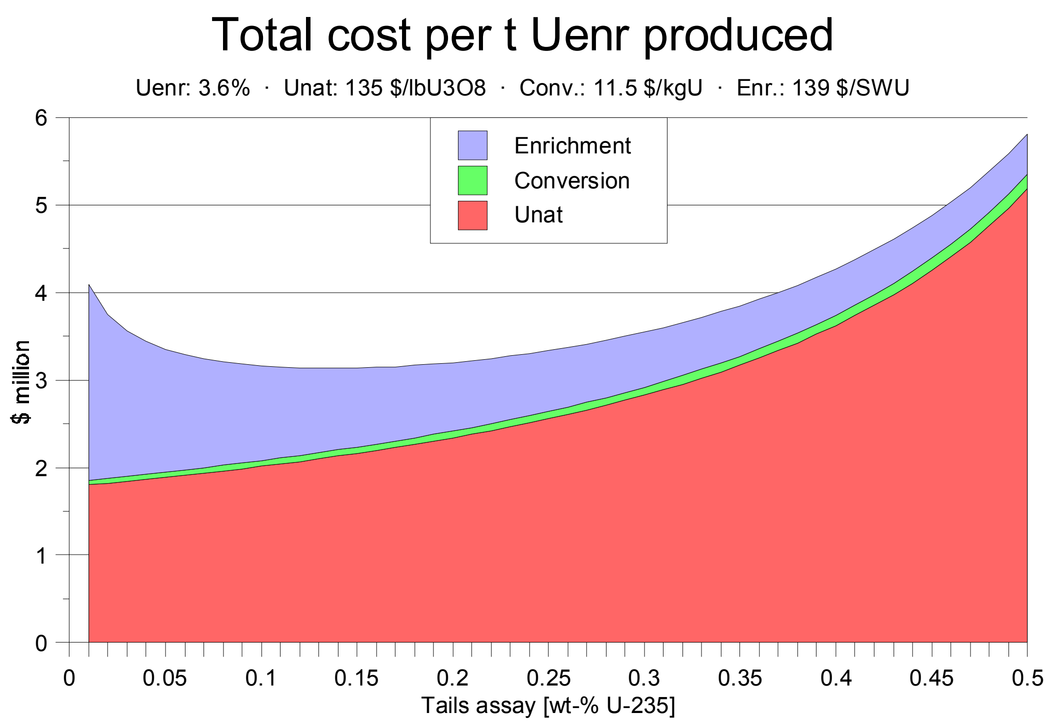


Fig. 3: Stacked cost at prices of June 4, 2007



Large amounts of depleted uranium tails are stored in so-called uranium hexafluoride cylinder yards next to the enrichment plants in various countries, waiting for a decision on any future use or final disposal. For the reasons shown, the tails generated at times of low prices for natural uranium usually have higher tails assays than those generated in times of high uranium prices. Now, in the times of steep jumps of the uranium price, the question is raised, whether older high-assay tails can be profitably processed to recover some of the residual U-235 contained. This process of re-feeding depleted uranium tails into an enrichment plant is called re-enrichment of tails, or tails-upgrading. By „stripping“ the tails to lower secondary tails assays, the process produces natural-equivalent and/or enriched uranium.

So far, re-enrichment has been performed in very special circumstances only: since 1996, depleted uranium tails generated by West European enrichers are being re-enriched in surplus centrifuge enrichment plants in Russia. The operators of enrichment plants in France (Eurodif), the United Kingdom, the Netherlands, and Germany (Urenco) are sending their depleted uranium tails to Russia for re-enrichment, mostly to natural-equivalent grade, and partly to reactor grade. In this case, a major aspect for the economic viability is the fact that the secondary tails generated from the re-enrichment remain in Russia, relieving Eurodif and Urenco from the tails disposition cost, see [Diehl_2004].
Recently, however, several proposals have been made to use also gaseous diffusion plants (GDP) for re-enrichment. In May 2005, the U.S. Department of Energy (DOE) made a first announcement for a pilot project for re-enrichment of 8,500 t of depleted uranium hexafluoride with an assay of 0.40 weight-% [DOE_2005a]. And, in May 2007, press reported about proposals to transfer up to 25,000 t of depleted uranium hexafluoride from DOE to USEC for re-enrichment; USEC is the operator of the Paducah GDP enrichment plant [HL_2007a] [NYT_2007a].

There are huge unused gaseous diffusion capacities available in the U.S., and more capacities are going to be made redundant in the U.S. and in France, once new gas centrifuge plants (currently under construction) will be commissioned.
While, so far, re-enrichment appeared to be reasonable only with gas centrifuge plants (if at all), the recent sharp rise of the uranium spot market price is changing the economic conditions now. The high specific energy consumption of the gaseous diffusion process no longer appears to be a limiting factor...

2. Availability of depleted uranium and surplus GDP enrichment capacities

Most of the depleted uranium ever generated in the U.S. is owned by the U.S. Department of Energy (DOE). Its depleted uranium inventory covers a wide range of tails assays (see Table 1 and Fig. 4, the latter also showing the storage locations of the material). These figures were published in 1992. By 1999, the inventory had increased by approx. 90,000 t U [DOE_1999c], though presumably not in the higher assay categories of interest here.
The data shows that a large amount of 94,886 t U in depleted uranium tails is available in the 0.31 - 0.50 wt-% U-235 category. This material - left from the early operation of the plants - is particularly useful for re-enrichment, since it requires less separative work than material with an assay in the 0.2 - 0.3% range, as typically generated in later years.
Some of the DOE depleted uranium inventory may be contaminated with unwanted minor isotopes once introduced into the cascades from recycling of uranium recovered from spent fuel

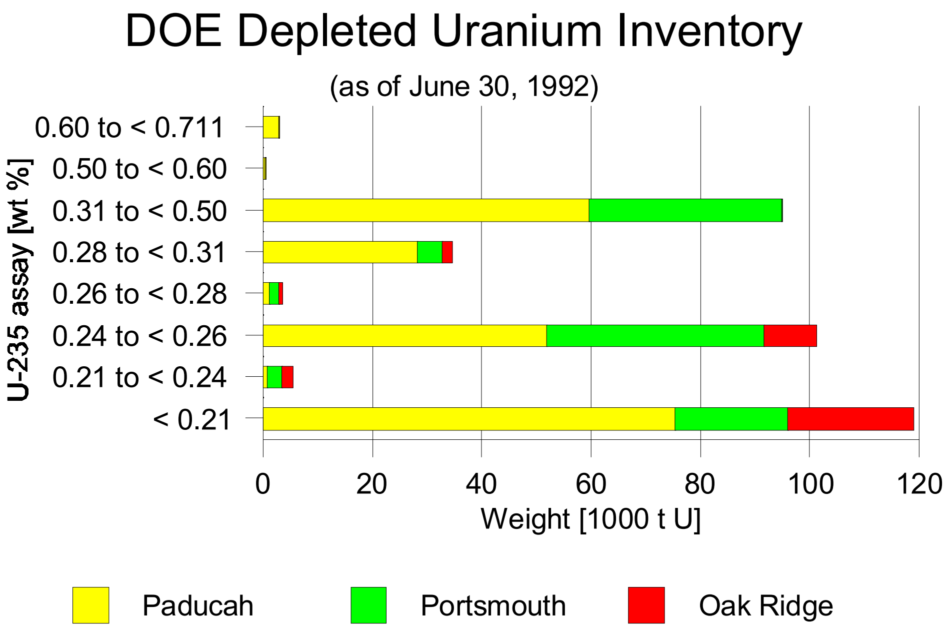
[Diehl_2005]. So, not all of the inventory might be suitable for re-enrichment to commercial fuel.

Table 1: U.S. DOE Depleted Uranium Inventory as of June 30, 1992 [t U]

Assay [wt-% U-235]								Total
< 0.21	0.21 - < 0.24	0.24 - < 0.26	0.26 - < 0.28	0.28 - < 0.31	0.31 - < 0.50	0.50 - < 0.60	0.60 - < 0.711	
118,784	5,271	101,064	3,483	34,428	94,886	506	2,931	361,352

t U = metric tonne uranium (multiply by 1.479 to obtain metric tonnes UF6)
Source: [DOE_1994]

Fig. 4:



At the end of 1999, France held DU inventories of 190,000 t U, only 50,000 t U of which were in the form of UF_6, while 140,000 t U were in the oxide form of U_3O_8 [NEA_2001], with tails assays in the 0.2 - 0.3 wt-% U-235 range. The deconversion to U_3O_8 was performed to ensure a safer long-term storage than possible with the form of UF_6. Therefore, any re-enrichment of DU tails held in the form of U_3O_8 would require prior conversion back to UF_6.

The gas diffusion enrichment capacities being and/or becoming available in the Western world are shown in Table 2. The Portsmouth gaseous diffusion plant in Piketon, Ohio, was placed in a cold standby mode effective May 11, 2001. ("cold standby" is a status achieved by removing UF_6 inventory from enrichment cells and maintaining those cells in a negative pressure, moisture-free environment; restart from "cold standby" would take 2 to 3 years). The Paducah, Kentucky, gaseous diffusion enrichment plant is currently operating at some fraction of its nominal capacity of 11.3 million SWU/a. Based on the 2006 electricity consumption of 10.5 TWh [KNews_2007a], the 2006 separation work can be estimated at 4.4 million SWU (assuming a power consumption of 2400 kWh/SWU). This represents a capacity utilization of 42%, leaving a capacity of 6.9 million SWU/a idle. The Paducah plant is to be replaced by USEC‘s American Centrifuge Plant being built at the Portsmouth site. In France, Eurodif‘s Georges Besse gaseous diffusion plant in Tricastin with a nominal capacity of 10.8 million SWU/a is currently producing 8 million SWU/a [CPDP_2004], resulting in a capacity utilization of 74%. The Georges Besse GDP is to be replaced by the Georges Besse II centrifuge plant, currently under construction near the old plant.

Table 2: Gaseous diffusion enrichment capacities becoming abundant

Plant	Operator	Current Status	Future Plans	Capacity [million SWU/a]	
				idle now	total
Portsmouth, Piketon OH, USA	USEC	cold standby	unknown	7.4	7.4
Paducah, KY, USA	USEC	operating below capacity	to be replaced by American Centrifuge Plant in Portsmouth	6.9	11.3
Georges Besse, Tricastin, France	Eurodif	operating	to be replaced by Georges Besse II centrifuge plant	2.8	10.8
				17.1	**29.5**

3. Characteristics of the re-enrichment process using GDPs

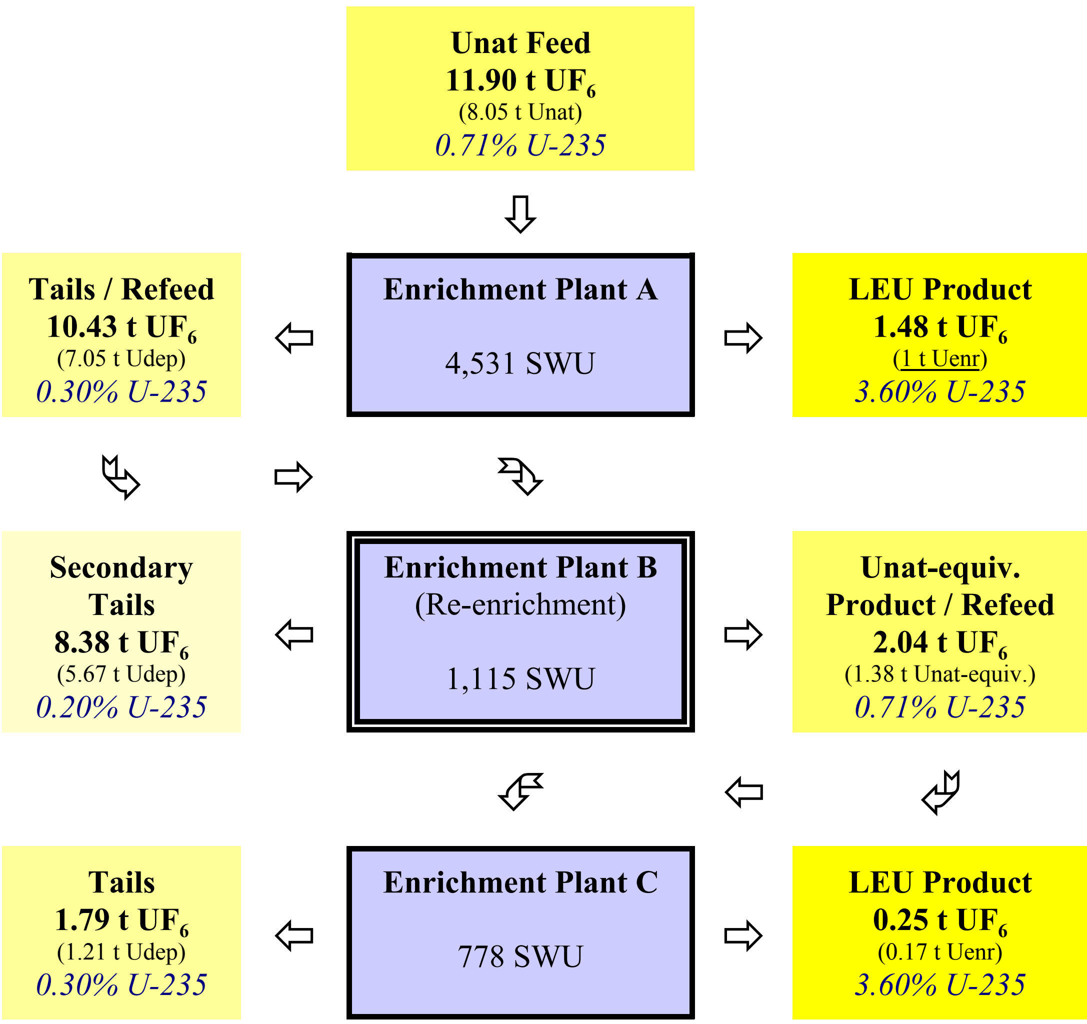
In this chapter, the following characteristics of the re-enrichment process are analyzed, based on mass balance calculations for typical cases: DU feed requirement, reduction in the amount of DU tails, separation work consumption, electricity consumption, and cost. The effect of variations of major parameters is demonstrated. First, an overview over the complete re-enrichment process chain is given. Next, the core process of DU tails re-enrichment to natural-equivalent uranium is analyzed, and then, the subsequent enrichment to reactor-grade uranium is included in the analysis.

3.1 Overview

Table 3 shows a typical mass balance for the complete process chain of re-enrichment of uranium. The figures are based on the amount of depleted uranium generated as a by-product from the production of 1 tonne of enriched uranium at an assay of 3.6 wt-% U-235 in Enrichment Plant A. The depleted uranium with a tails assay of 0.3 wt-% U-235 is fed into Enrichment Plant B for re-enrichment to natural assay (0.71 wt-% U-235). The re-enriched natural-equivalent uranium is then further enriched (in Enrichment Plant C) to the assay required for nuclear fuel (here again 3.6 wt-% U-235). The tails generated from the re-enrichment in Plant B are assumed to have a tails assay of 0.2 wt-% U-235.

In this typical example, the total re-enrichment process (in Plant B and C) increases the amount of reactor-grade LEU (produced from a given amount of natural uranium feed) by 17%, at the expense of a 42% increase in separation work.

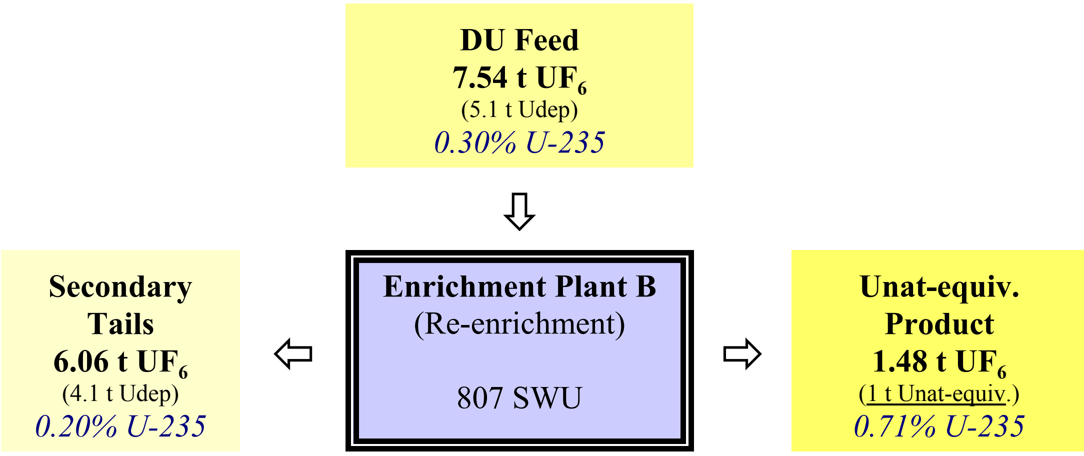
Table 3: Mass balance for re-enrichment of uranium per t Uenr (original)



3.2 Mass balance per unit natural-equivalent uranium recovered

Table 4 focuses on the typical mass balance of the core re-enrichment process in Enrichment Plant B; here, the figures are shown per tonne natural-equivalent uranium recovered. All assays are unchanged from the previous example.

Table 4: Mass balance for re-enrichment of uranium per t Unat-equiv. (re-enriched)



The following observations can be made from the mass balance:

DU tails reduction

The amount of secondary tails generated is equivalent to the DU feed processed minus the amount of natural-equivalent uranium recovered.

- In the typical example of Table 4, the re-enrichment process leads to a 20% reduction of the amount of tails. (More tails are generated in the subsequent enrichment to LEU, however, see below.)

DU feed requirement

- In the typical example of Table 4, the amount of DU feed required is 5.1 t U per tonne of natural-equivalent uranium recovered.

Fig. 5 shows the effect of parameter variations on the DU feed requirement: it presents the DU feed required per tonne Unat-equivalent recovered, depending on DU feed assay and secondary tails assay.

- The amount of DU feed required increases excessively with increasing secondary tails assays. Or, expressed the other way round: the amount of natural-equivalent uranium recoverable from a given amount of DU feed decreases rapidly with increasing secondary tails assays.

SWU consumption

' In the typical example of Table 4, a separation work of 0.807 SWU is required to recover 1 kg of natural-equivalent uranium.

Fig. 6 shows the effect of parameter variations on the SWU consumption: it presents the separative work (in SWU) required per kg U replaced by re-enrichment, depending on DU feed assay and secondary tails assay.

' The separative work required increases excessively with decreasing secondary tails assays. Or, expressed the other way round: the amount of natural-equivalent uranium recoverable using a given amount of separation work decreases rapidly with decreasing secondary tails assays.

Electricity consumption

Assuming a specific electricity consumption of approx. 2,400 kWh/SWU for gaseous diffusion, the actual electricity consumption can be determined:

' In the typical example of Table 4, an electricity consumption of 1,937 kWh is required to recover 1 kg of natural-equivalent uranium. This is by far higher than the energy required to produce the uranium by conventional mining, milling, and conversion. Corresponding to the SWU consumption, the electricity consumption increases excessively for decreasing secondary tails assays.

Cost analysis

Figs. 7 - 9 compare the unit cost for the production of natural-equivalent UF_6 from re-enrichment of depleted uranium tails to that of natural UF_6 from conversion of fresh natural uranium. The results are based on the following assumptions:

- Re-enrichment: availability of the DU feed as UF_6 at no cost; enrichment price of US$ 139/SWU; bonus for avoided DU management cost of US$ 10/kg UF_6 avoided (resulting from the reduction in the total amount of DU tails).
- Natural uranium: conversion price of US$ 11.5/kg U.

Fig. 7 shows the cost for re-enriched natural-equivalent UF_6 as percentage of the cost for natural UF_6, for a DU feed assay of 0.3%, depending on secondary tails assay and price of natural uranium.

' Re-enrichment starts to make sense only for uranium prices above US$ 25/lb U_3O_8. For the current extremely high spot market price of uranium (UxC: US$ 135/lb U_3O_8 as of June 4, 2007), re-enrichment of depleted uranium tails is cheaper than fresh uranium for almost any reasonable secondary tails assay.

Fig. 8 shows the same for a DU feed assay of 0.4%.

Fig. 9 is derived from the two previous figures. It shows the secondary tails assay, for which the re-enrichment cost is equal to the cost for fresh natural uranium, depending on DU feed assay and price of natural uranium. For secondary tails assays higher than those shown, re-enrichment is cheaper than fresh uranium, and vice versa.

Fig. 5:

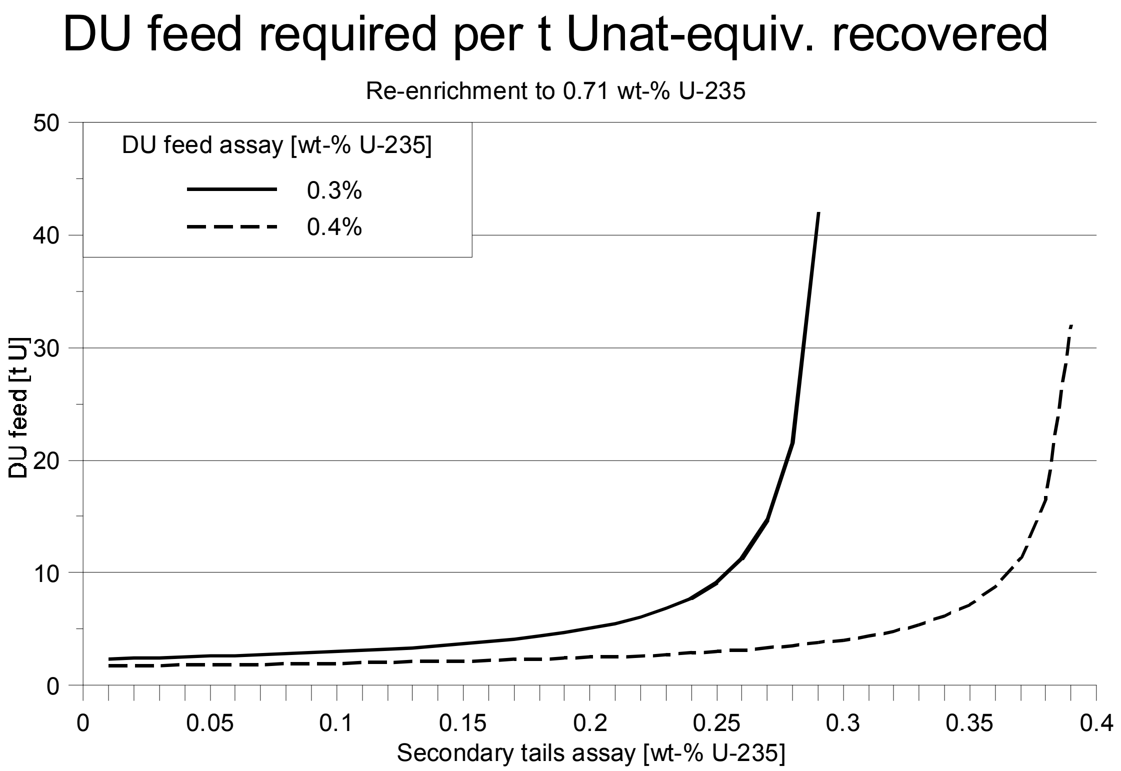

DU feed required per t Unat-equiv. recovered
Re-enrichment to 0.71 wt-% U-235
DU feed assay [wt-% U-235]
0.3%
0.4%
DU feed [t U]
Secondary tails assay [wt-% U-235]
0
10
20
30
40
50
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Fig. 6:

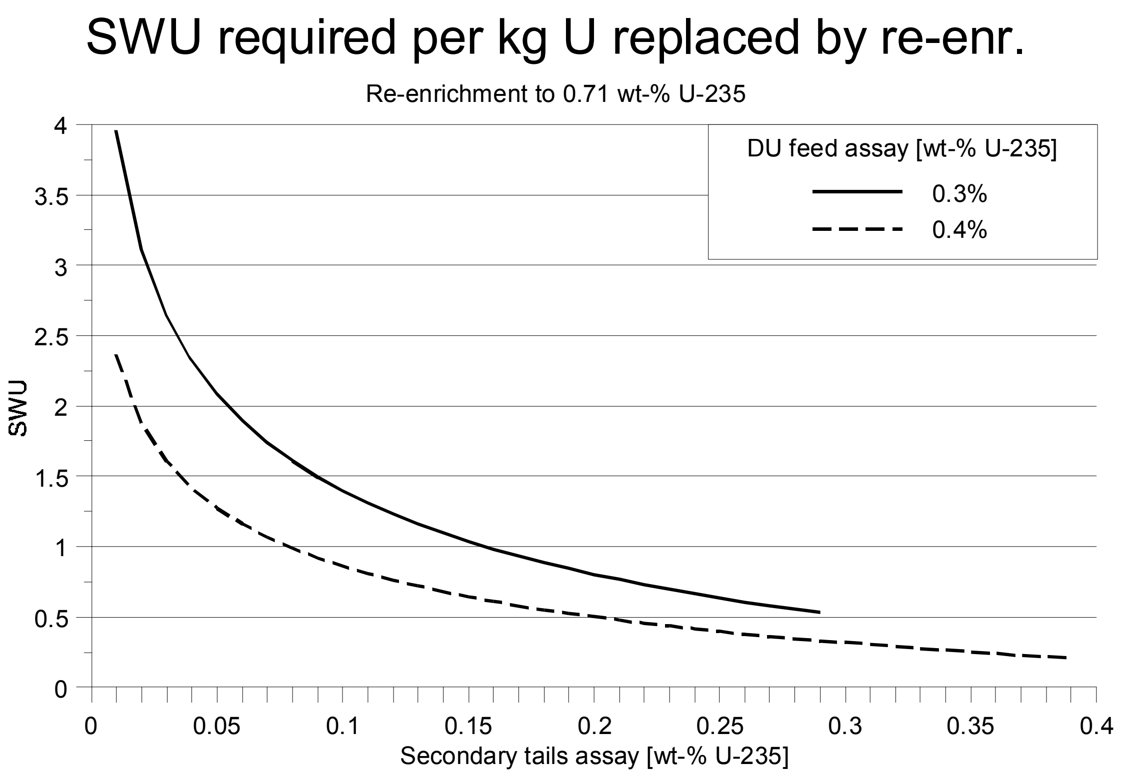

SWU required per kg U replaced by re-enr.
Re-enrichment to 0.71 wt-% U-235
DU feed assay [wt-% U-235]
0.3%
0.4%
SWU
Secondary tails assay [wt-% U-235]
0
0.5
1
1.5
2
2.5
3
3.5
4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Fig. 7:

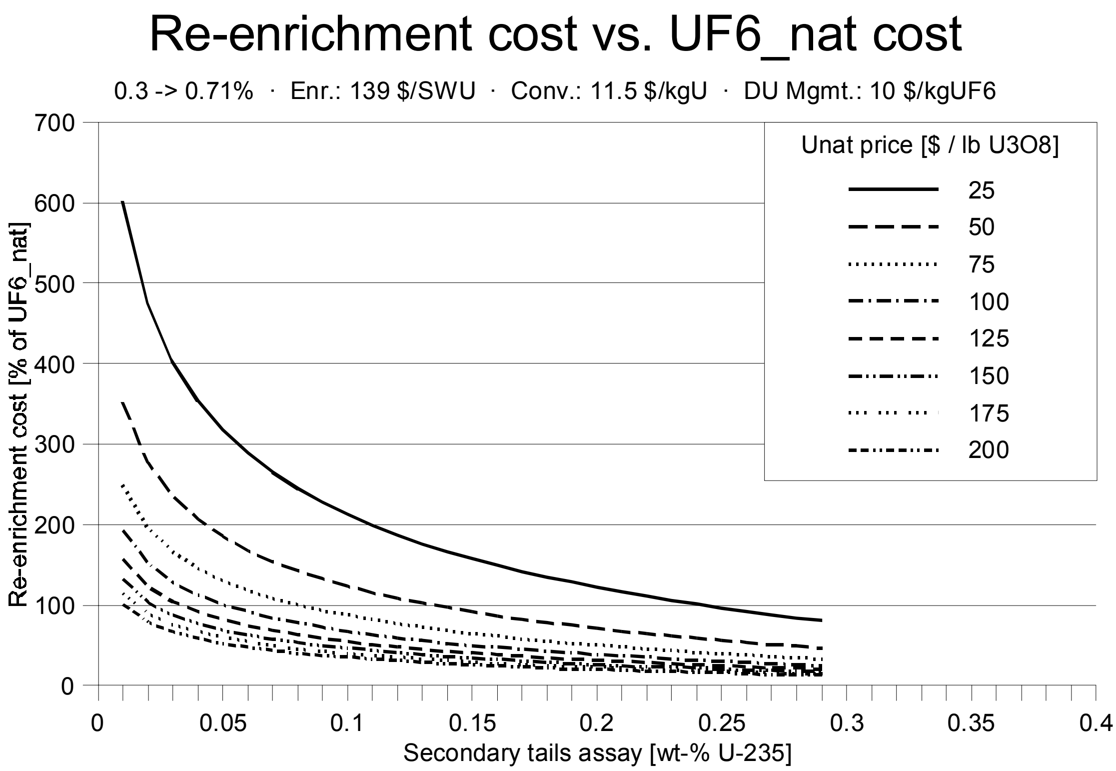

Re-enrichment cost vs. UF6_nat cost
0.3 -> 0.71% · Enr.: 139 $/SWU · Conv.: 11.5 $/kgU · DU Mgmt.: 10 $/kgUF6
Re-enrichment cost [% of UF6_nat]
Secondary tails assay [wt-% U-235]
Unat price [$ / lb U3O8]
25
50
75
100
125
150
175
200
0
100
200
300
400
500
600
700
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Fig. 8:

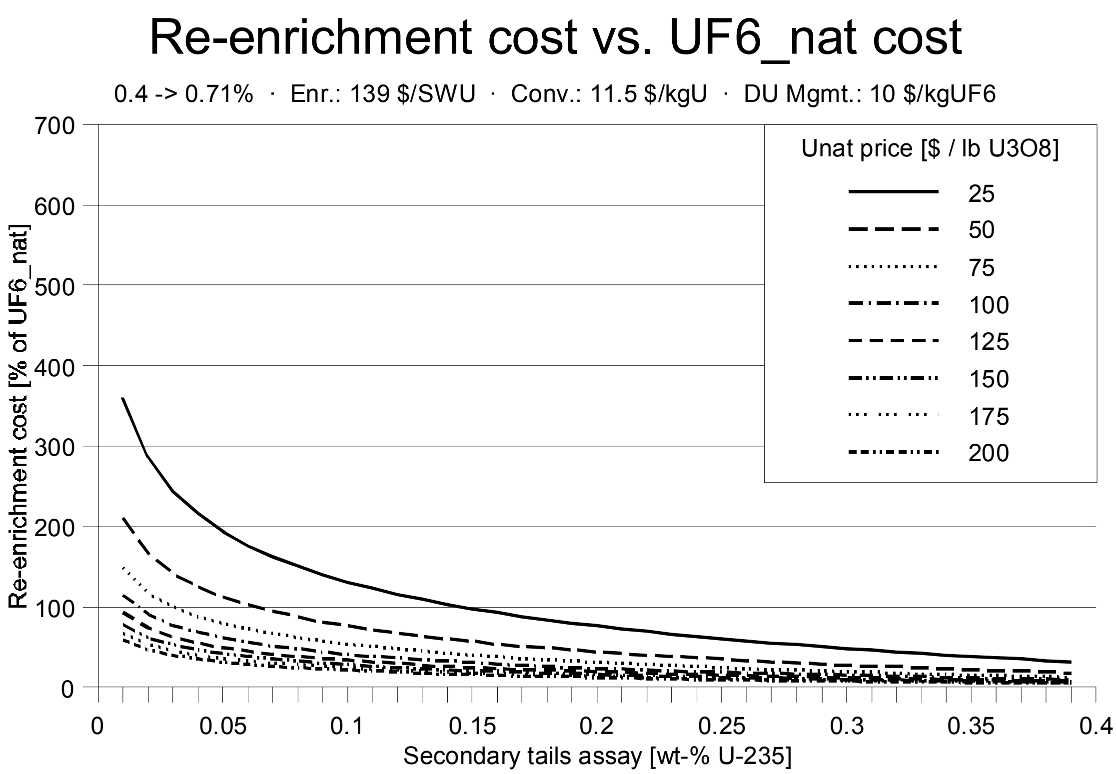
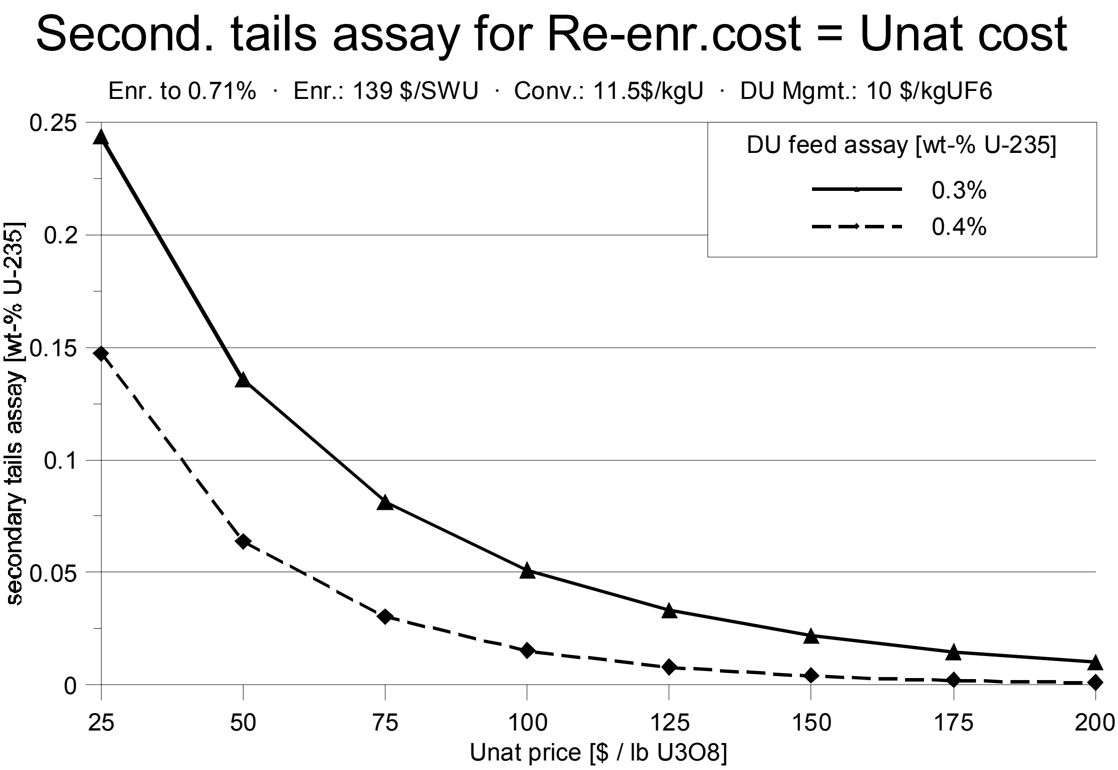

Re-enrichment cost vs. UF6_nat cost
0.4 -> 0.71% · Enr.: 139 $/SWU · Conv.: 11.5 $/kgU · DU Mgmt.: 10 $/kgUF6
Re-enrichment cost [% of UF6_nat]
Secondary tails assay [wt-% U-235]
Unat price [$ / lb U3O8]
25
50
75
100
125
150
175
200
0
100
200
300
400
500
600
700
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Fig. 9:



3.3 Mass balance per unit low-enriched uranium recovered

Table 5 extends the mass balance to the step generating nuclear fuel-grade uranium from the natural-equivalent uranium recovered by re-enrichment. It shows the mass balance per tonne low enriched uranium (LEU) recovered by the whole process. The re-enriched natural-equivalent uranium is further enriched (in Enrichment Plant C) to the assay required for nuclear fuel (here 3.6 wt-% U-235). The tails generated from the enrichment in Plant C are assumed to have an assay of 0.3 wt-% U-235.
The following observations can be made:

DU tails reduction

' Through the re-enrichment process, the amount of DU tails decreases by a mere 2.4% in this typical example.

SWU consumption

' In this typical example, the separative work required for re-enrichment of the DU feed to natural-equivalent assay is 43% higher than that required for the further enrichment from natural-equivalent to LEU assay. The total SWU consumption thus is almost 2.5 times that required for straight enrichment of natural uranium.

Fig. 10 shows the effect of parameter variations on the SWU consumption: it presents the total separative work (in SWU) used in Enrichment Plants B and C per unit enriched uranium Uenr (LEU) recovered, depending on DU feed assay and secondary tails assay, expressed as multiple of the separative work used in the reference case, where the same amount of enriched uranium is produced by straight enrichment of natural uranium.

- At 0.3% DU feed assay, the separative work is at least approx. twice that required for straight enrichment of natural uranium, and it increases excessively for lower secondary tails assays. At 0.4% DU feed assay, the figures are somewhat lower.

Electricity consumption

- Since enrichment by gaseous diffusion with its very high specific electricity consumption of approx. 2,400 kWh/SWU represents the main sink of energy in the nuclear fuel production process, re-enrichment more than doubles the energy requirements for nuclear fuel production.
- The situation worsens dramatically, if re-enrichment in a GDP plant is compared to straight enrichment in a centrifuge plant (at 50 kWh/SWU or less): in the typical example, the re-enrichment thus would consume more than 72 times the electricity needed for straight enrichment of natural uranium. Apparently, the current re-enrichment proposals are pointing exactly towards this direction: normal enrichment is to be switched to energy-saving centrifuge technology, while the old GDP plants are left for re-enrichment.
- If the electricity used for the GDP plant is generated in coal-fired power plants, the CO_2 emission also would experience increase rates similar to those of electricity consumption.

Fig. 11 shows the effect of parameter variations on the electricity consumption: it presents the total electricity consumption used in Enrichment Plants B and C per unit enriched uranium Uenr (LEU) recovered, depending on DU feed assay and secondary tails assay, expressed as multiple of the electricity used in the reference case, where the same amount of enriched uranium is produced by straight enrichment of natural uranium.
For the re-enrichment case, a gaseous diffusion plant with a specific electricity consumption of 2400 kWh/SWU is assumed for Plant B, and a centrifuge plant with a specific consumption of 50 kWh/SWU for Plant C. For the reference case, also a centrifuge enrichment plant with a specific consumption of 50 kWh/SWU is assumed.

- At 0.3% DU feed assay, the electricity consumption is at least approx. 48 times that required for straight enrichment of natural uranium, and it increases excessively for lower secondary tails assays. At 0.4% DU feed assay, the figures are somewhat lower.

Table 5: Mass balance for re-enrichment of uranium per t Uenr (re-enriched)

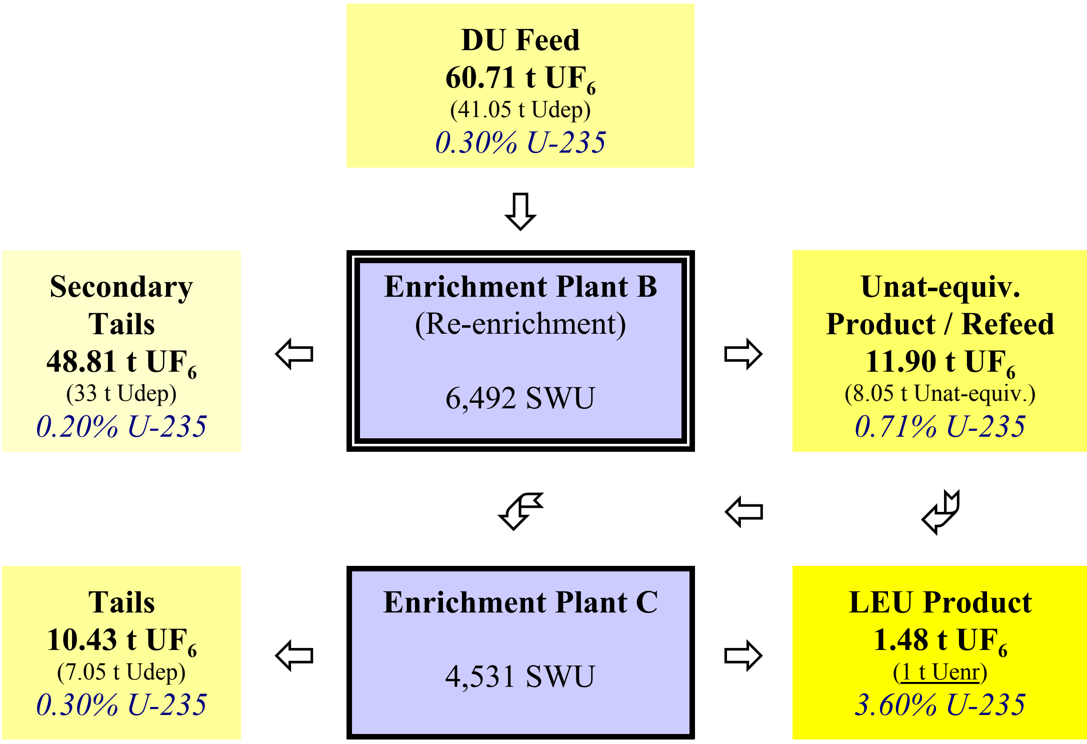


Fig. 10:

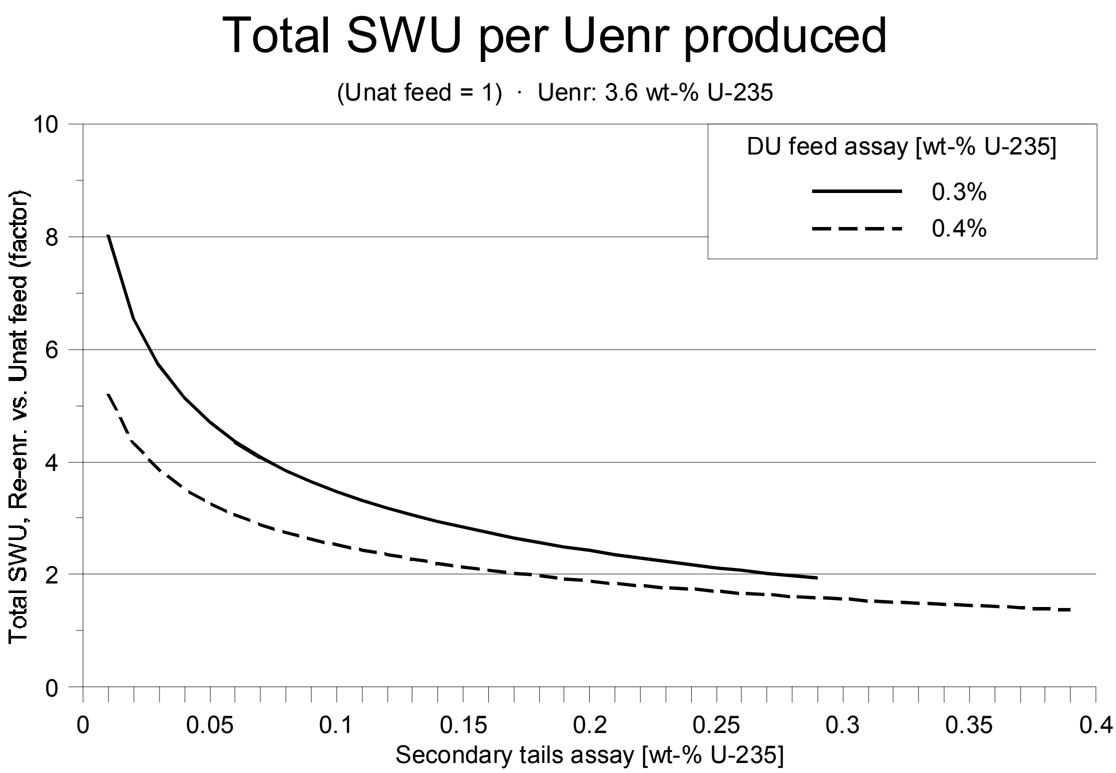
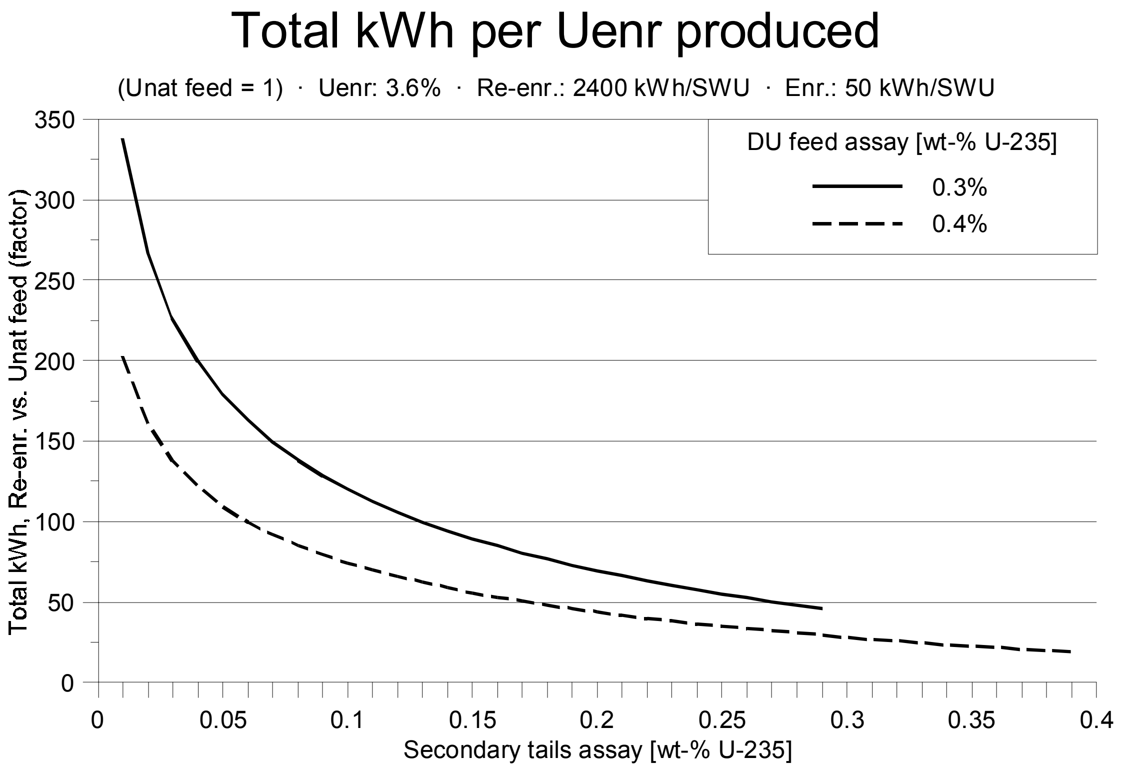


Fig. 11:



3.4 Summary of the characteristics of uranium re-enrichment

' For a given amount of DU feed, the maximum amount of re-enriched uranium is obtained by selecting a very low secondary tails assay. This requires the spending of a very large amount of separative work (subject to SWU availability), however.

' For a given SWU capacity, the maximum amount of re-enriched uranium is obtained by selecting a relatively high secondary tails assay, only slightly lower than the DU feed assay. This requires the processing of very large amounts of DU feed, however.

For a typical example (0.3% DU feed assay and tails assay, 0.2% secondary tails assay, 3.6% product assay), the following results are obtained:

' For a given amount of natural uranium processed in the first place, the amount of reactor-grade LEU increases by 17%, at the expense of a 42% increase in separation work.

' Per unit LEU produced, the amount of DU tails decreases by a mere 2.4%; the total SWU consumption is almost 2.5 times that required for straight enrichment of natural uranium and increases excessively for lower secondary tails assays. The electricity consumption, also, is almost 2.5 times that required for straight enrichment of natural uranium, supposed the same enrichment technology is assumed for re-enrichment and straight enrichment. If, however, re-enrichment in a GDP is compared to straight enrichment in a centrifuge plant, electricity consumption of re-enrichment would be more than 72 times that required for straight enrichment.

- A cost analysis shows that for the current high spot market price of uranium (US$ 135/lb U_3O_8 as of June 4, 2007), re-enrichment of depleted uranium tails is cheaper than fresh uranium for almost any reasonable secondary tails assay.

For re-enrichment of tails with a high assay of 0.4%, less separation work is required to obtain the same amount of product (with other assays unchanged):

- For a given amount of natural uranium processed in the first place, the amount of reactor-grade LEU increases by 45%, at the expense of a 103% increase in separation work.

- Per unit LEU produced, the amount of DU tails decreases by just 5%; the total SWU consumption is almost 1.9 times that required for straight enrichment of natural uranium and increases excessively for lower secondary tails assays. The electricity consumption, also, is almost 1.9 times that required for straight enrichment of natural uranium, supposed the same enrichment technology is assumed for re-enrichment and straight enrichment. If, however, re-enrichment in a GDP is compared to straight enrichment in a centrifuge plant, electricity consumption of re-enrichment would be more than 43 times that required for straight enrichment.

4. Re-enrichment scenarios using gaseous diffusion plants

In this chapter, the observed characteristics of the re-enrichment process are applied to various scenarios, some of which have been announced or proposed recently, while others are hypothetical.

4.1 Pilot Project: Processing of 8,500 t UF_6 U.S. DOE high-assay tails

„A pilot project was initiated in May 2005 between DOE and the Bonneville Power Administration (BPA). The project will process 8,500 MT of DUF_6 with an assay 0.40 wt% and greater over a maximum two year period. The project is estimated to produce a maximum of 1,900 MTU of natural equivalent UF_6.“ [DOE_2005a]
(MT = metric tonne, DUF_6 = depleted uranium hexafluoride, MTU = metric tonne uranium)

If a DU feed assay of 0.4 wt-% U-235 is assumed, processing of 8,500 t UF_6 to 1,900 t U in natural-equivalent UF_6 requires 0.75 million SWU and generates 5,728 t UF_6 tails at an assay of approx. 0.25 wt-% U-235.

4.2 Processing of 25,000 t UF_6 U.S. DOE high-assay tails

With the same parameters assumed (i.e. DU feed assay 0.4 wt-% U-235; secondary tails assay 0.25 wt-% U-235), processing of 25,000 t UF_6 would produce 5,512 t U in natural-equivalent UF_6, thereby requiring 2.21 million SWU, and leaving behind 16,848 t UF_6 of secondary tails.

4.3 Processing of U.S.DOE DU stock with complete Portsmouth GDP capacity

If the total capacity of the Portsmouth gas diffusion plant (currently maintained in cold standby) of 7.4 million SWU/a would be made available for re-enrichment of DU feed to natural-equivalent uranium, the results in Table 6 could be obtained. For each of the major DU feed assay categories of DOE's DU stocks, alternative results are presented for various secondary tails assays.

- Depending on the secondary tails assays selected, processing of the complete DU stocks listed would require between approx. 6 and 26 years (thereby consuming approx. 43 to 194 million SWU).
- The annual amount of natural-equivalent uranium recovered would be between 18,461 and 2,139 t U/a (for comparison: in 2005, the U.S. demand for uranium was 22,875 t U, while production from domestic mines was just 1,039 t U).
- The total amount of natural-equivalent uranium recovered over the whole operating period would come up to between 55,198 and 109,806 t U (for comparison: in 2005, the world demand for uranium was 66,840 t U).
- At the spot price of US$ 135 / lb U_3O_8 (as of June 4, 2007), the uranium recoverable from the tails represents a value of US$ 19 - 39 billion.

After all of the DOE DU stocks would have been processed, the DU tails generated by the current enrichment operation could be re-enriched. However, the amount of DU tails currently being generated in the U.S. is only 6,845 t U/a (based on 4.4 million SWU/a, 0.3% tails assay, 3.6% product assay), while Portsmouth could process 16,139 - 106,652 t U/a of such tails (depending on secondary tails assay). Even when taking into account the envisaged capacity increase by construction of the LES enrichment plant in New Mexico, the re-enrichment capacity of the Portsmouth GDP would be much larger than the annual amount of tails generated in the U.S., for all secondary tails assays shown in Table 6.

4.4 Processing of U.S.DOE DU stock with idle part of Paducah GDP capacity

Similar calculations can be performed for the presumed 6.9 million SWU of currently idle diffusion capacities at the Paducah enrichment plant (in this case, it is assumed that the Paducah plant is the only source of re-enrichment capacity and the Portsmouth GDP remains in cold standby). Paducah's annual figures of DU feed and Unat-equivalent production would be 7% lower, while the time required for the processing of the material would be 7% higher than for the Portsmouth GDP. The total Unat-equivalent product figures would remain unchanged, since the same assay parameters were assumed.

Table 6: Re-enr. of DOE DU stock with Portsmouth GDP capacity (7.4 million SWU/a)

DU Stock [t U] [1]	DU Feed assay [wt-% U-235]	Second. tails assay [wt-% U-235] [2]	Annual DU Feed [t U/a]	Full-capacity years [3]	Annual Unat-eqv. Product [t U/a]	Total Unat-eqv. Product [t U]
94,886	**0.40**	**0.25**	56,613	1.7	18,461	30,941
		0.20	37,407	2.5	14,669	37,209
		0.15	25,622	3.7	11,438	42,358
		0.10	17,415	5.4	8,565	46,667
34,428	**0.30**	**0.25**	106,652	0.3	11,593	3,742
		0.20	46,793	0.7	9,175	6,751
		0.15	26,572	1.3	7,117	9,221
		0.10	16,139	2.1	5,292	11,289
101,064	**0.25**	**0.20**	74,309	1.4	7,285	9,908
		0.15	31,542	3.2	5,632	18,046
		0.10	16,950	6.0	4,168	24,852
118,784	**0.20**	**0.15**	49,432	2.4	4,414	10,607
		0.10	19,806	6.0	3,247	19,473
		0.05	9,411	12.6	2,139	26,998

[1]) from Table 1 (simplified)
[2]) alternatively
[3]) full-capacity years required for processing of DU Stock amounts given in the first column

4.5 Processing of U.S.DOE DU stock with complete Paducah GDP capacity

Similar calculations can be performed for the total 11.3 million SWU of diffusion capacities to be made redundant at the Paducah enrichment plant, once the American Centrifuge Plant is operational (in this case, it is assumed that the Paducah plant is the only source of re-enrichment capacity and the Portsmouth GDP remains in cold standby). According to the higher capacity, Paducah‘s annual figures of DU feed and Unat-equivalent production would be 53% higher, while the full-capacity years required for the processing of the material would be 35% lower than for the Portsmouth GDP. The total Unat-equivalent product figures would remain unchanged, since the same assay parameters were assumed.

4.6 Processing of France‘s DU stock with Georges Besse GDP

If the total capacity of the Georges Besse gas diffusion plant of 10.8 million SWU/a would be made available for re-enrichment of DU feed to natural-equivalent uranium (once the Georges Besse II centrifuge enrichment plant is in full operation), the results in Table 7 could be obtained. Since the assay distribution of France‘s DU stock is unknown, three DU assays are shown that are (other than in Table 6) alternatively used for the whole inventory. For each of the DU feed assay alternatives shown, alternative results are presented for various secondary tails assays.

- Depending on the actual DU stock assay and on the secondary tails assays selected, processing of the complete DU stock listed would require between approx. 1.2 and 14 years (thereby consuming approx. 13 to 150 million SWU).
- The annual amount of natural-equiv. uranium recovered would be betw. 16,919 and 3,122 t U/a (for comparison: in 2005, France‘s demand was 7,185 t U).
- The total amount of natural-equivalent uranium recovered over the whole operating period would come up to between 16,963 and 62,295 t U (for comparison: in 2005, the world demand for uranium was 66,840 t U).
- At the spot price of US$ 135 / lb U_3O_8 (as of June 4, 2007), the uranium recoverable from the tails represents a value of US$ 6 - 22 billion.

The annual amount of DU tails currently generated in France is 16,802 t U/a (assuming Georges Besse GDP at full capacity of 10.8 million SWU, 0.3% tails assay, 3.6% product assay).
The re-enrichment capacity of the Georges Besse GDP would be much larger than the annual amount of tails currently generated in France for most of the secondary tails assays shown.

Table 7: Re-enrich. of France‘s DU stock with Georges Besse GDP (10.8 mln. SWU/a)

DU Stock [t U] [1])	DU Feed assay [wt-% U-235] [2])	Second. tails assay [wt-% U-235] [2])	Annual DU Feed [t U/a]	Full-capacity years [3])	Annual Unat-eqv. Product [t U/a]	Total Unat-eqv. Product [t U]
190,000	0.30	0.25	155,654	1.2	16,919	20,652
		0.20	68,292	2.8	13,391	37,256
		0.15	38,780	4.9	10,388	50,895
		0.10	23,555	8.1	7,723	62,295
	0.25	0.20	108,451	1.8	10,632	18,627
		0.15	46,034	4.1	8,220	33,927
		0.10	24,738	7.7	6,083	46,720
	0.20	0.15	72,144	2.6	6,441	16,963
		0.10	28,907	6.6	4,739	31,149
		0.05	13,735	13.8	3,122	43,187

[1]) material currently held in the form of U_3O_8 requires prior conversion back to UF_6.
[2]) alternatively
[3]) full-capacity years required for processing of DU Stock amount given in the first column

5. Conclusions

The surplus gaseous diffusion enrichment capacities currently available and/or soon to become abundant in the USA would be suitable to re-enrich DOE‘s stock of depleted uranium within roughly one decade. The total amount of natural-equivalent uranium recoverable would be in the order of the world uranium demand of one year. Particularly interesting is the processing of the available high-assay materials with assays around 0.4%.

The surplus gaseous diffusion enrichment capacities soon to become abundant in France would be suitable to re-enrich France‘s stock of depleted uranium within roughly one decade. However, most of the material first would have to be converted to UF_6, since it has been deconverted to U_3O_8 for safer long-term storage. The total amount of natural-equivalent uranium recoverable would be in the order of one half of the world uranium demand of one year.

Higher total amounts of recovered natural-equivalent uranium are obtainable, if lower secondary tails assays are chosen, requiring longer operation of the plant (and thus the expense of more separation work and electricity), and vice versa.

At the current high spot market price of uranium (US$ 135/lb U_3O_8 as of June 4, 2007), the cost of re-enrichment of depleted uranium tails is cheaper than fresh uranium for almost any reasonable secondary tails assay chosen.

Per unit low-enriched uranium (LEU) produced, the amount of DU tails decreases only marginally, thus not easing the problem of finding a solution for the final disposition of the tails.

The total separative work consumption per unit LEU produced is at least approx. twice that required for straight enrichment of natural uranium and increases excessively for lower secondary tails assays.

The electricity consumption per unit LEU produced, also, is at least approx. twice that required for straight enrichment of natural uranium. If, however, the re-enrichment in a gaseous diffusion plant is compared to straight enrichment in a centrifuge plant, the electricity consumption of re-enrichment would be more than approx. 40 times that required for straight enrichment, still increasing excessively for lower secondary tails assays. If the electricity used for the GDP plant is generated in coal-fired power plants, the CO_2 emission also would experience increase rates similar to those of electricity consumption.

Glossary

* = term has an extra entry in the glossary

assay: concentration of an isotope (U-235 subsumed, if not otherwise indicated) in uranium, usually given as weight-percent

conversion: conversion of uranium from one chemical form into another one (usually *U_3O_8 to *UF_6, if not otherwise indicated)

depleted uranium (DU): uranium (of any chemical form) with concentration of isotope U-235 lower than in *natural uranium (i.e. < 0.711 weight-%)

DOE: U.S. Department of Energy

DU: *depleted uranium

enriched uranium: uranium (of any chemical form) with concentration of isotope U-235 higher than in *natural uranium (i.e. > 0.711 weight-%)

enrichment: process of increasing the concentration of the fissile isotope U-235 in uranium, usually by physical processes, such as gaseous diffusion or gas centrifugation; produces a product stream of *enriched uranium and a by-product stream of *depleted uranium (tails)

feed: uranium introduced into the enrichment cascade as *UF_6

GDP: Gaseous Diffusion Plant, *enrichment plant using the gaseous diffusion process

LEU: *Low Enriched Uranium

low enriched uranium (LEU): uranium with an U-235 *assay > 0.711% and < 20% (as used in Light Water Reactors - *LWR)

LWR: Light Water Reactor, such as Boiling Water Reactor and Pressurized Water Reactor, requires *enriched uranium with U-235 *assay of 3-5% as fuel

natural uranium: uranium (of any chemical form) of natural isotopic composition, containing 0.711 weight-% (equal to 0.72 atom-%) U-235

„natural-equivalent“ uranium: term used in this paper for uranium with natural concentration of U-235 obtained from *re-enrichment of *tails; the concentration of the minor isotope U-234 is lower than in real *Unat; sometimes also called „pseudo-natural“ uranium.

NRC: U.S. Nuclear Regulatory Commission

product: enriched (or re-enriched) *UF_6 produced in the *enrichment process

re-enrichment: use of *depleted uranium rather than *natural uranium as *feed for the *enrichment process; not to be mistaken for the *recycling* of uranium from spent fuel.

secondary tails: *tails generated from *re-enrichment of tails

SWU: Separative Work Unit

t: metric tonne = 1000 kg

t U: metric tonne uranium contained in some compound

tails: by-product from *enrichment of uranium: *depleted uranium in the form of *UF_6; not to be mistaken for uranium mill *tailings* - the waste arising from uranium extraction from ore

tails upgrading: equivalent to *re-enrichment of *tails

Udep: *depleted uranium

Uenr: *enriched uranium

Unat: *natural uranium

Unat-equiv.: *„natural-equivalent“ uranium

UF_6: **uranium hexafluoride** (chemical form required for enrichment by gaseous diffusion or centrifugation)
1 t UF_6 contains 0.676 t U, while 1 t U is contained in 1.479 t UF_6

U_3O_8: **triuranium octoxide** (chemical from extracted from ore)
1 t U_3O_8 contains 0.848 t U, while1 t U is contained in 1.179 t U_3O_8
1 lb U_3O_8 contains 0.385 kg U, while 1 kg U is contained in 2.6 lbs U_3O_8

USEC: U.S. Enrichment Corporation, operator of the gaseous diffusion enrichment plants at Paducah, KY, and Portsmouth (Piketon, OH)

wt-%: weight-percent

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