Re-enrichment of West European Depleted Uranium Tails in Russia

prepared for Ecodefense Russia by

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Contents

Abstract

Since 1996, depleted uranium tails from West European enrichers Urenco and Eurodif are being sent to Russia for re-enrichment. In Russia, the imported tails are, instead of natural uranium, fed into surplus enrichment cascades. The product obtained from re-enrichment is mostly natural-equivalent uranium plus some reactor-grade low-enriched uranium. These products are sent back to Urenco and Eurodif, while the secondary tails generated remain in Russia, where they are re-enriched further to obtain more natural-equivalent uranium and/or slightly enriched uranium. The latter is then used as blendstock for the downblending of surplus highly-enriched weapons-grade uranium into reactor-grade low-enriched uranium. The ultimate tails left, still comprising at least two thirds of the amount imported, remain in Russia with unknown fate.
This paper collects the scarce information available on this strange business, sets up a mass balance for it, looks into its odd economics and the policies behind it. Three driving forces are identified: Urenco‘s and Eurodif‘s aim to avoid tails disposal cost, Russia‘s shortage of uranium deposits, and the trade restrictions for Russian enrichment services.

1. Depleted uranium: the long-neglected waste problem

1.1. Uranium enrichment: the origin of depleted uranium

For the use of uranium as fuel in a light water reactor (LWR), the percentage of the fissile uranium isotope U-235 has to be raised from its value of 0.71% in natural uranium to a reactor grade of 3 - 5%. The enrichment technologies commercially available at present are the gaseous diffusion process and the centrifuge process. Both of them require the prior conversion of the uranium to the gaseous form of uranium hexafluoride (UF_6). The product stream of enriched UF_6 obtained is then converted to the form of UO_2 for further processing to nuclear fuel assemblies. Table 2 shows the - in parts outdated - installed enrichment capacities of the world.

The enrichment process not only produces the enriched product, but it also generates a waste stream („tails“) of uranium hexafluoride depleted in U-235 ("depleted uranium" - DU), typically down to 0.2% - 0.35%. The residual concentration of U-235 (the "tails assay") in this depleted uranium waste is a parameter that can be adjusted to economical needs, depending on the cost of fresh natural uranium (expressed in \$ per lb U_3O_8) and on the enrichment cost (expressed in \$ per Separative Work Unit - SWU). Table 1 shows a typical mass balance for the enrichment process. It can be seen that the depleted uranium waste stream is approx. seven times the enriched uranium product stream. 88% of the feed mass ends up in the tails. For typical isotopic compositions of uranium, see Table 3.

Table 1: Typical mass balance of uranium enrichment
(per t of enriched uranium, 3.6% product assay, 0.3% tails assay)

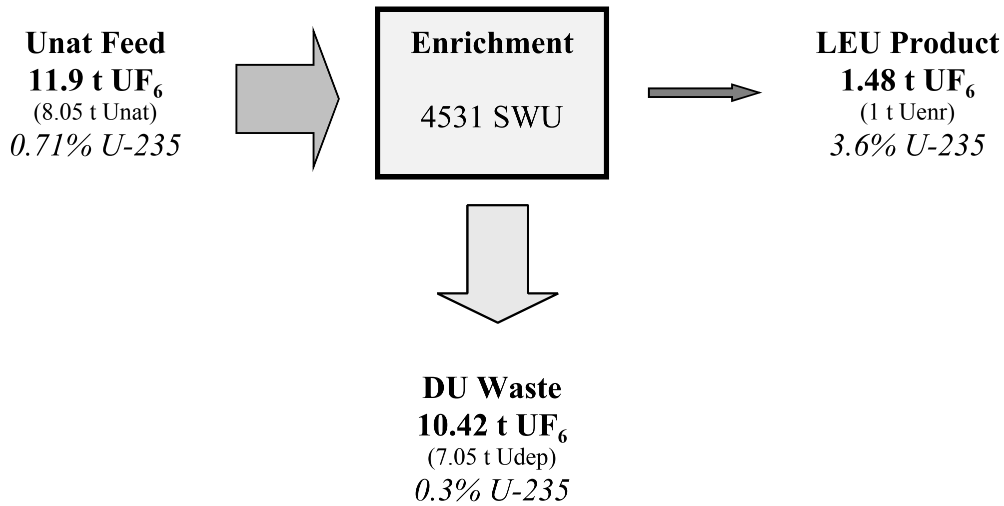


Table 2: World Uranium Enrichment Capacities

Country	Owner / Controller	Plant Name / Location	Capacity [a] [million SWU]
Gaseous Diffusion Plants			
China	CNNC	Lanzhou	0.90
France	Eurodif	Tricastin	10.80
United States	U.S. Enrichment Corp.	Paducah, Kentucky	11.30
Subtotal Diffusion Plants			*23.00*
Centrifuge Plants			
China	CNNC	Hanzhong	0.50
		Lanzhou	0.50
Germany	Urenco	Gronau	1.46
Japan	JNC	Ningyo Toge	0.20
	Japan Nuclear Fuel Limited (JNFL)	Rokkasho-mura	1.05
Netherlands	Urenco	Almelo	1.95
Russia	Rosatom	Urals Electrochemical Integrated Enterprise (UEIE), Novouralsk (formerly Sverdlovsk-44, near Ekaterinburg)	7.00
		Siberian Chemical Combine (SKhK), Seversk (formerly Tomsk-7)	4.00
		Electrochemical Plant (ECP), Zelenogorsk (formerly Krasnoyarsk-45)	3.00
		Angarsk Electrolytic Chemical Combine (AEKhK), Angarsk	1.00
UK	Urenco	Capenhurst	2.44
Subtotal Centrifuge Plants			*23.10*
TOTAL			*46.10*

[a] Nominal capacity

Table 3: Typical isotopic compositions of uranium [weight-percent]

	U-235	U-234	U-238
Depleted uranium - DU (0.2%)	0.200%	0.0009%	99.799%
Natural uranium	0.711%	0.0053%	99.284%
Low enriched uranium - LEU (3.5%)	3.500%	0.0288%	96.471%
Highly enriched uranium - HEU (93%)	93.000%	1.0100%	5.990%

Note: DU, LEU and HEU from enrichment of natural uranium.

1.2. Cylinder storage of depleted uranium hexafluoride

Amounts stored

Most of the depleted uranium generated to date is being stored as UF_6 in steel cylinders in the open air in so-called cylinder yards located adjacent to the enrichment plants. The cylinders contain up to 12.5 t of UF_6. An inventory of depleted uranium stocks of the world is given in Table 4. These figures are, however, incomplete and rather outdated. In the U.S. alone, for example, approximately 739,000 t U of depleted uranium, stored as UF_6 in 61,400 cylinders, have accumulated until April 2003, rather than the 480,000 t U listed. [USEC Apr. 11, 2003]

Portsmouth (Ohio) Depleted Uranium Cylinder Storage Yard (U.S. DOE)

Table 4: World Stocks of Depleted Uranium
(t U as UF_6, as of end 1999, unless otherwise indicated)

	Stocks [t U]	**Notes**
USA	480,000	As of mid-2000
Russia	460,000	10,000 t of which as metal and oxides
France	190,000	140,000 t of which as U_3O_8
United Kingdom	30,000	non-Urenco only (BNFL)
Urenco	16,000	in UK, Netherlands, and Germany
Japan	10,000	As of February 2001
China	2,000	As of end 2000
Germany	300	non-Urenco only (ANF)
Korea, Rep.	200	
South Africa	73	mostly metal and oxides
World Total	1,188,573	

Source: [NEA 2001]

Hazards of DU storage in cylinder yards

At ambient temperature, UF_6 is a crystalline solid, but at a temperature of 56.4°C already, it sublimates (becomes a gas). Chemically, UF_6 is very reactive: with water (atmospheric humidity!) it forms the extremely corrosive hydrofluoric acid and the highly toxic uranyl fluoride (UO_2F_2).
In case of an accidental release of UF_6, the hydrofluoric acid causes skin burns, and, after inhalation, damages the lung. Further health hazards from intake result from the chemical toxicity of the uranium to the kidneys, and from the radiation hazard of the uranium (an alpha emitter).
Under normal conditions, the external radiation hazard is a concern for workers in the cylinder yards. While the external radiation hazard from the uranium itself is rather low, decay products growing in within a few months emit some gamma radiation. In addition, some neutron radiation is emitted from so-called nuclear (alpha,n)-reactions, initiated in the fluorine component of the UF_6 by the uranium‘s alpha radiation. Near cylinders holding depleted uranium, up to 20% of the external radiation exposure can be due to the neutron radiation [Urenco 2002].
In the storage yards, the cylinders are subject to corrosion. The integrity of the cylinders must therefore be monitored and the painting must be refreshed from time to time. This maintenance work requires moving of the cylinders, causing further hazards from breaching of corroded cylinders, and from handling errors.
If UF_6 cylinders are engulfed in externally fueled fires for more than 30 - 60 minutes, sudden releases of large amounts of UF_6 can occur, once a cylinder breaches. If the whole contents of a cylinder is released during a fire, lethal air concentrations of toxic substances can occur within

distances of 500 - 1000 meters.
As a worst-case scenario, the crash of an airplane into a cylinder yard must be assumed.

1.3. Depleted uranium: waste or resource?

Depleted uranium with a tails assay of 0.3% still contains 42% of the fissile uranium isotope U-235 found in natural uranium. Further extraction of the U-235 would be technically possible, but not economically feasible under current cost and market conditions.
According to the proponents of nuclear power, changes in the market or new enrichment technologies might allow for a future economical recovery of the residual U-235. The depleted uranium should therefore not be seen as a waste that has to be disposed of, but as a future resource that should be stored indefinitely.
However, industry‘s and regulators' views are not exactly conclusive regarding this question:

- On Nov. 5, 1998, a French appeals court, revoking a lower tribunal's decision, ruled that depleted uranium is no waste, but a "*directly usable raw material* that is effectively used for multiple uses" - and the DU therefore may be stored indefinitely in the form of U_3O_8 in purpose-built storage buildings, as requested by the license applicant (Eurodif‘s parent company Cogéma, see below).
- On Sep. 8, 2004, U.S. NRC staff presented its view before the U.S. Nuclear Regulatory Commission that depleted uranium *is a low level waste* - and the DU therefore may be transferred to the Department of Energy (DOE) for disposition, as requested by the license applicant (Urenco‘s U.S. subsidiary Louisiana Energy Services - LES). A final decision of the NRC is still pending at the time of this writing.
- On Sept. 26, 2001, the Texas Department of Health *approved the disposal of DU counterweights at a land burial facility not even licensed for disposal of radioactive waste*, as requested by the license applicant (Philotechnics Ltd.).

Amazingly, the position of Urenco‘s U.S. subsidiary is diametrically opposed to that of Cogéma in France, but it is the key to get access to the cheapest tails disposition route available in the U.S. And, it appears that the views of the regulators are more depending on the respective desires of the nuclear industry, rather than on some general concept.

1.4. Possible uses of depleted uranium

Historically, uranium has been used as a coloring matter in pottery. More recent civilian uses include the use of uranium as a steel alloying constituent, and the use of several uranium compounds in chemical processes, for example as a catalyst. For its high density of 18.9 g/cm^3 (67% higher than that of lead and slightly lower than that of tungsten) uranium can be used in dense metal applications such as counterweights or flywheels. The first 550 Boeing 747 aircrafts built, utilized depleted uranium weights for mass balance of outboard elevator and upper rudder assemblies, for example. But this use of depleted uranium in the form of uranium metal also included drawbacks: over 20% of these weights were corroded at each major aircraft overhaul and had to be reprocessed, although nickel and cadmium plated [USNRC 1983]. In more recent aircraft designs, however, the use of counterweights has been minimized due to advanced design technology. Military dense metal applications of depleted uranium include the

use for penetrators and for tank armor.
During the production process of uranium metal applications, the pyrophoric behaviour of small uranium metal particles constitutes a problem. These particles, such as finely divided metallic saw turnings and chips, sawdust, and abrasive saw sludge are capable of spontaneous ignition, and have caused many incidents. Inhalation of dust from fires involving uranium metal can cause high radiation doses.
Another possible use of depleted uranium based on its high density is the use in radiation shields: though an alpha-radioactive material itself, it is suitable for shielding penetrating gamma-radiation better than lead.
For all of the uses mentioned it doesn't matter, other than for use as nuclear fuel, that the uranium is depleted in U-235.

To date, none of the civilian uses of depleted uranium has brought an appreciable decrease of the existing stockpiles of this material; not even the military use could achieve this, though currently the largest consumer. In the U.S. therefore, the Department of Energy (DOE), alerted by the increasing maintenance problems of its cylinder yards, is now performing the first steps towards a large-scale civilian use of depleted uranium. As of July 1993, DOE‘s inventory was 559,000 metric tonnes of depleted UF_6 stored in 46,422 cylinders; and in 1998 DOE assumed responsibility for a further 137,000 metric tonnes (11,400 cylinders) produced by USEC. DOE's preferred alternative is to use the entire inventory of material in the form of metal or oxide, mainly for radiation shielding in casks for spent fuel and high-level waste, but also for other industrial uses to be developed. The depleted uranium, now contained at a few sites, then would be dispersed over a wide range of products. DOE now plans to build two plants, at costs of nearly $200 million each, to convert the UF_6 to more stable forms, suitable for manufacturing into marketable products, or for disposal.

1.5. Long-term storage or disposal

The portion of the depleted uranium for which no use can be identified must be disposed of, or must be safely stored in the long term for possible future uses.
For long-term storage or disposal, the depleted UF_6 must be converted to a less reactive chemical form: candidates are UF_4, U_3O_8, and UO_2. UF_4 has the advantage of being easily re-convertible to UF_6, while U_3O_8 is the most stable form, also existing in natural minerals.

The depleted uranium long-term storage project at Bessines (France)

France's nuclear fuel company Cogéma was the first to go ahead with the concept of long-term storage of its depleted uranium in oxide form. For this purpose, it is storing the depleted uranium as U_3O_8 at the site of the former uranium mill of Bessines-sur-Gartempe (Haute Vienne) near Limoges. Following an appeals court decision approving the storage on the basis that the DU represents a raw material rather than a waste, Cogéma sent the first DU shipment to Bessines on Nov. 12, 1998.
Cogéma‘s depleted uranium is generated at the Eurodif Tricastin gaseous diffusion enrichment plant in the Rhône valley. Its residual contents of U-235 (tails assay) is 0.2 to 0.3%. For storage, the UF_6 is converted to the chemically more stable form of U_3O_8 in „Usine W“ of Cogéma's

Pierrelatte facility. Then it is transported by rail to the Bessines site and stored as a powder in iron containers. The containers (8.5 or 11 t each) are being stored in 11 purpose-built buildings. Each building can store 2500 containers; the projected total storage capacity is 199,900 t U, at a total investment cost of EUR 9.15 million over a period of 15 years. The maximum dose that an individual would be exposed to at the fence of the facility, is calculated at 0.7 mSv per year.

Urenco‘s Gronau depleted uranium storage project

Meanwhile, Urenco too, is planing the storage of depleted uranium as oxide: Together with the application for a capacity-increase of its Gronau, Germany, enrichment plant to 4 million SWU/year, Urenco filed an application for the construction of two storage buildings for its depleted uranium waste. The depleted uranium is currently being stored as uranium hexafluoride in cylinder yards next to the plant with a licensed capacity of 38,100 t UF_6. For storage, the depleted uranium is to be converted to the more stable form of U_3O_8 at the Pierrelatte facility in France. The storage buildings are to be designed for a capacity of 50,000 t U as U_3O_8. [Urenco 2002]

Urenco‘s Capenhurst depleted uranium storage project

At its Capenhurst (UK) site, Urenco plans to hold the tails as UF_6 until 2020. Then, deconversion to U_3O_8 shall start at a rate of 3000 tU/year through to 2042. The U_3O_8 will be stored in „suitably engineered facilities“ on the Capenhurst site. Transfer of the U_3O_8 to the final repository is scheduled to begin in 2120 (!), when the repository becomes available, and to end in 2142. [HSE 2004]

Disposal cost

For the ultimate disposal of depleted uranium, only estimates can be made, since no large tails disposal is in existence yet. Nearly all depleted uranium generated so far is temporarily stored and waiting for a decision about its ultimate disposition.
A „Cost analysis report for the long term management of depleted uranium hexafluoride“ performed by the U.S. Department of Energy (DOE) analyzes the costs for a number of management options. Among these, the most promising one from an environmental protection view is the disposal of the depleted uranium as U_3O_8 in cemented form in a mine. The cost estimates for the specific cost of this option are \$4.57 per kg UF_6, see Table 5 [Elayat 1997]. But, even for this option it is unclear, how it shall meet the requirements for long-term containment of the uranium and its decay products growing in (such as radium).
In a 2003 filing with the U.S. Nuclear Regulatory Commission (NRC), U.S. enricher USEC presented an even lower estimate for its tails disposition cost in 2004: deconversion and disposal cost of 2.99 US\$ per kg U, plus transport cost of 0.21 US\$ per kg U [USEC 2003]. This corresponds to 2.02 and 0.14 US\$ per kg UF_6, respectively.
In its balance sheets, Urenco makes provisions of 7.03 EUR per kg U for the deposition of its tails (see below). For the German branch of Urenco, disposal in the proposed Gorleben HLW deposit must be assumed, although the depleted uranium would be suitable for disposal in a LLW deposit. But the activity limits for the only LLW deposit in Germany, the proposed „Schacht Konrad“ deposit, would only allow for the disposal of a total of approx. 100 t of

depleted uranium [Wingender 1994].

Table 5: Estimated discounted disposition cost for depleted UF_6 (U.S. DOE)
(Option: disposal as cemented U_3O_8 in a mine, dry defluorination process w/AHF Prod.)

	Total Cost for 560,000 t UF_6	**Specific Cost**	
	[US$ million]	[US$/kg UF_6]	[US$/kg U]
Continued Storage	197	0.35	0.52
Transport	702	1.25	1.85
Conversion	267	0.48	0.71
Disposal	1395	2.49	3.69
TOTAL	2561	4.57	6.77

Source: [Elayat 1997], specific cost added

For the Gorleben deposit, the final disposal cost can be estimated at approx. 10.2 US$ per kg UF_6 for bulk disposal as U_3O_8, or 22.5 US$ per kg UF_6 for cemented disposal as U_3O_8 (or 15.1 resp. 33.3 US$ per kg U contained in UF_6).
(This figure is based on the following assumptions: The storage cost for a 200-liter barrel at the proposed Gorleben HLW deposit is estimated at 7670 EUR; the volume needed for disposal of the tails as U_3O_8 in barrels is estimated at 550 litre/t U_3O_8 for cemented disposal and 250 litre/t U_3O_8 for bulk disposal; conversion cost of 1.6 EUR per kg UF_6; 1 US$ = 0.79 EUR).

The comparison of the tails disposition cost estimates (see Table 6) shows an extraordinarily wide range. And, it becomes clear that the tails disposition cost for Urenco‘s German branch are prohibitive, since they would claim up to nearly half of the proceeds from the enrichment business. Urenco‘s German branch (at least) thus is in an urgency to get rid of its tails whatever happens; otherwise it would not be able to survive in the market.

Table 6: Summary of tails disposition cost estimates
(deconversion + disposal only, no discounting)

	Tails disposition cost estimate [a]) [US$/kg UF_6]	**Percentage of enrichment price** [b])
USEC	2.02	4.2%
US DOE (as U_3O_8, cemented, in a mine)	2.97	6.2%
Urenco provision (as U_3O_8)	6.02	12.6%
Gorleben (as U_3O_8, bulk)	10.20	21.4%
Gorleben (as U_3O_8, cemented)	22.50	47.0%

[a]) based on 1 US$ = 0.79 EUR

[b]) based on 110 US$/SWU , tails at 2.3 kg UF_6/SWU (for product assay of 3.6% and tails assay of 0.3%)

2. Re-enrichment of depleted uranium tails

2.1. Tails enrichment - the deal

Surprisingly, the recovery of the residual U-235 contained in the depleted uranium no longer is a matter of the future: it is being practiced since 1996 already, although neither new highly-efficient enrichment technologies have entered the market, nor enrichment cost have decreased. Depleted uranium, mainly from European uranium enrichers Urenco and Eurodif, is being enriched in Russia. Urenco is operating three centrifuge enrichment plants in Capenhurst (United Kingdom), Almelo (The Netherlands), and Gronau (Germany), while Eurodif, a subsidiary of Cogéma (Areva Group), is operating the Tricastin diffusion enrichment plant at Pierrelatte (France), see Table 2 on p.3. For ownership details on Urenco, see Table 7, and on Eurodif, see Table 8.
Surplus capacities at the centrifuge enrichment plant of Rosatom‘s Ural Electrochemical Integrated Plant (UEChK, formerly Sverdlovsk-44) at Novouralsk near Ekaterinburg are being used for the enrichment of tails rather than natural uranium. Rosatom is the Russian Federal Atomic Energy Agency (previously Minatom). While further depleting ("stripping") the depleted uranium, it produces uranium of natural contents (0.71%) in U-235. It thus *re-enriches* or *upgrades* the tails to natural-equivalent U-235 grade. This product is then delivered back to Urenco and Eurodif for further enrichment to reactor grade.

Table 7: Ownership details of Urenco Ltd.

Share	Owner	Parent
33.3%	BNFL Enrichment	100% British Nuclear Fuels plc. (BNFL)
33.3%	Ultra-Centrifuge Nederland N.V. (UNC)	
33.3%	Uranit GmbH	50 % RWE Power AG
		50% E.ON Kernkraft GmbH

Note: the British and Dutch holdings are ultimately owned by the respective governments

Table 8: Ownership details of Eurodif SA

Share	Owner	Parent
44.653%	COGEMA (Areva Group) (France)	
25%	SOFIDIF	60% COGEMA (Areva Group) (France)
		40% OEAI (Iran)
11.111%	ENUSA (Spain)	
11.111%	SYNATOM (Belgium)	
8.125%	ENEA (Italy)	

Note: total holdings of COGEMA in Eurodif: 59.653%

Available facts on the Re-enrichment business

Details on the re-enrichment business, though it is currently taking place at large scale, are hardly obtainable. In Russia, all related information is confidential; and, the West-European enrichment companies involved, Urenco and Eurodif, are not very communicative, to put it politely. In its recent annual reports, Urenco not even discloses its annual production figure, nor the capacity break down for its facilities, not to speak about other data of interest, such as amount and assays of tails produced.
Only some scattered figures can be found here and there, most of which can be traced back to information originally obtained from the company RWE Nukem. Moreover, in some cases it is not clear whether mass figures are meant for the amount of uranium hexafluoride, or the uranium contained. On the other hand, the physics of the uranium enrichment process are well established, and allow to determine (or at least guess) many missing parameters.

These are the - mostly unconfirmed - data found in the public domain:

1) The re-enrichment deals between Urenco / Eurodif and Rosatom:
- Urenco and Eurodif each send 7,000 t U in tails per year to Russia for enrichment [NF, May 12, 2003]. For the tails sent by Urenco's German branch, a break down of the destinations within Russia is available, see Table 9.
- Urenco's tails have an assay of 0.3%, Eurodif's an assay of 0.35%. [NF, May 12, 2003]
- Urenco and Eurodif each get back 1,100 t U of re-enriched natural-equivalent uranium (Uneq) contained in UF_6. [NF, May 12, 2003]
- Approximately half of the total of 2,200 t U of re-enriched Uneq received by Urenco and Eurodif is used by EU utilities (see Table 19 on p.18), the rest is being exported. [ESA AR 1998]
- Eurodif, in addition, gets back 130 t U in UF_6 of uranium re-enriched to 3.5%. [NF, May 12, 2003]
- Rosatom spends a total of 2.58 million SWU on this re-enrichment deal for Urenco and Eurodif. [Bukharin 2004]
- Rosatom does not charge the market price for the SWU it spends, but presumably a cost price of $20 per SWU. [Bukharin 2004]
- The secondary tails generated by the re-enrichment process remain in Russia. [BT-Drs. 13/8810] [Bukharin 2004]

2) Rosatom's additional exploitation of the secondary tails from the Urenco / Eurodif deals:
- The secondary tails are re-enriched further by Rosatom on its own account.
- Rosatom strips them down to a tails assay of 0.1%. [Bukharin 2004]
- Rosatom this way obtains a further 3300 t U [?] of re-enriched natural-equivalent uranium per year, which it can use or sell on its own account; Rosatom uses at least part of this material for the production of blendstock (assay 1.5%) for the downblending of HEU (see below). [NF, May 12, 2003] [Bukharin 2004]

3) Overall re-enrichment performed by Rosatom on Urenco / Eurodif tails:
- Rosatom spends a total of 7 million SWU annually on all re-enrichment done under 1) and 2). [Bukharin 2004]

Note: In addition, Rosatom also re-enriches tails from its own DU stocks; this process is not covered here, however.

A detailed analysis (see Annex) shows that, in fact, these data allow to establish a plausible mass balance of the whole re-enrichment business, with one major exception: the figure of 3300 tons of re-enriched uranium obtained by Rosatom on its own account has to be taken as the amount of UF_6, not that of the uranium contained (2231 t U). Some minor differences with other figures can possibly be explained by generous rounding. All further discussion in this paper is based on that estimated mass balance.

Table 9: German exports of depleted uranium to Russia for re-enrichment [t U as UF_6]

Year	Destination			Total
	Ural Electro-chemical Plant, Novouralsk	**Siberian Group, Seversk**	**Angarsk Electrolizing, Angarsk**	
1991 - 1995	No exports			
1996				502.395
1997				2404.585
1998	1893.100	201.069	133.956	2228.125
1999	1574.520	569.312	284.777	2428.608
2000	1305.896	200.740	251.273	1757.909
2001, 1st Q.		284.569	133.863	418.433

Source: BT-Drs. 14/5638 (March 23, 2001), 14/6692 (July 16, 2001)

2.2. Mass balance of the re-enrichment process

The key features of the mass balance are presented as a flowchart in Table 10 for the re-enrichment performed on Urenco‘s tails, and in Table 11 for that performed on Eurodif‘s tails.

Analysis from a tails disposition perspective

One important aspect of the re-enrichment deal with Russia is that it opens a disposition route for the tails generated by Urenco and Eurodif.
To produce the amount of 7000 t U of tails that is sent to Russia, Urenco would have to spend approx. 4.5 million SWU. This exactly equals Urenco‘s production figure for 2000, but in subsequent years the production was higher due to capacity increases, see Table 12.
The production figures for the subsequent years are not given in Urenco‘s annual reports, only the increase rates are given: 2001: +11%; 2002: +11%; 2003: +10% [Urenco AR 2000 - 2003].
The resulting production figures are shown in Table 13, together with the estimated amounts of tails generated.
So, for 2000, the amount of tails produced by Urenco was equivalent to the amount delivered to Russia for re-enrichment. In the later years, tails production exceeded the deliveries to Russia.

Table 10: Annual mass balance estimate for re-enrichment of Urenco's tails

Unat Feed **11821 t UF_6** (7993 t Unat) *0.71% U-235*	→	**Urenco** enrichment 4.5 million SWU	→	**LEU Product** **1469 t UF_6** (993 t Uenr) *3.6% U-235*
DU Waste / Refeed **10352 t UF_6** (7000 t Udep) *0.3% U-235*	→	**Rosatom** re-enrichment Step 1 (on Urenco's account) 0.79 million SWU	→	**Uneq Product** **1619 t UF_6** (1095 t Uneq) *0.71% U-235*
DU Waste / Refeed **8733 t UF_6** (5905 t Udep) *0.224% U-235*	→	**Rosatom** re-enrichment Step 2 (on its own account) Opt.N: 2.42 mln SWU Opt.B: 3.37 mln SWU	→	**Product** Option N: **Uneq** **1775 t UF_6** (1200 t Uneq) *0.71% U-235* Option B: **LEU** **774 t UF_6** (523 t Uenr) *1.5% U-235*

↓

DU Waste

Option N:	Option B:
6958 t UF_6	**7960 t UF_6**
(4705 t Udep)	(5382 t Udep)
0.1% U-235	*0.1% U-235*

Product produced by Rosatom on its own account:
Option N: „Natural-equivalent" uranium (0.71% assay), or
Option B: Blendstock with 1.5% assay, for HEU downblending

<u>Table 11</u>: Annual mass balance estimate for re-enrichment of Eurodif's tails

Unat Feed **11642 t UF_6** (7872 t Unat) *0.71% U-235*	**Eurodif** enrichment 3.6 million SWU	**LEU Product** **1290 t UF_6** (872 t Uenr) *3.6% U-235*
44% →	**Rosatom** re-enrichment Step 1a (on Eurodif's account) 1.21 million SWU	**LEU Product** **192 t UF_6** (130 t Uenr) *3.5% U-235*
DU Waste / Refeed **10352 t UF_6** (7000 t Udep) *0.35% U-235*		
56% →	**Rosatom** re-enrichment Step 1b (on Eurodif's account) 0.67 million SWU	**Uneq Product** **1633 t UF_6** (1105 t Uneq) *0.71% U-235*
DU Waste / Refeed **8526 t UF_6** (5765 t Udep) *0.21% U-235*	**Rosatom** re-enrichment Step 2 (on its own account) <u>Opt.N</u>: 2.25 mln SWU <u>Opt.B</u>: 3.07 mln SWU	**Product** <u>Option N</u>: **Uneq** **1538 t UF_6** (1040 t Uneq) *0.71% U-235* <u>Option B</u>: **LEU** **670 t UF_6** (453 t Uenr) *1.5% U-235*

DU Waste

<u>Option N</u>:	<u>Option B</u>:
6989 t UF_6	**7857 t UF_6**
(4726 t Udep)	(5312 t Udep)
0.1% U-235	*0.1% U-235*

Product produced by Rosatom on its own account:
<u>Option N</u>: „Natural-equivalent" uranium (0.71% assay), or
<u>Option B</u>: Blendstock with 1.5% assay, for HEU downblending

Table 12: Urenco‘s nominal enrichment capacity at end of year [million SWU]

Year	Capenhurst	Almelo	Gronau	TOTAL
2000	2	1.5	1.3	4.8
2001				5.25
2002	2.44	1.95	1.46	5.85
2003				6.5

Source: [Urenco AR 2000 - 2003]

Table 13: Estimate of tails generated by Urenco
(assuming product assay of 3.6% and tails assay of 0.30%)

Year	**Production** [million SWU]	**Tails** [t U as UF_6]
2000	4.5	7001
2001	5	7779
2002	5.54	8619
2003	6.1	9490

Nevertheless, Urenco‘s tails stocks were decreasing even in those later years.
The data available on Urenco‘s tails stocks is only rather imcomplete:

- As of June 30, 1994, Urenco‘s DU inventory was 8,000 t in Capenhurst (UK), 12,000 t in Almelo (NL), and 3,800 t in Gronau (Germany), totaling 23,800 t (t U?). [NF Nov. 7, 1994]
- As of end 1999, the total tails inventory was 16,000 t U. [NEA 2001]
- In 2001 alone, total tails stocks held on all Urenco sites were reduced by around 8%, and in 2002 by a further 5%. [Urenco AR 2001 & 2002]
- As of Feb. 2003, only 1,000 t were left over from the tails stock of 3,800 t reported for Urenco‘s Gronau (Germany) site as of June 30, 1994. [NF Feb. 17, 2003]

The financial provisions made by Urenco for the tails disposition in its balance sheets (see Table 14) presumably roughly reflect the changes in its tails inventory. The decrease in 2001 and 2002 can be recognized, however the sharp 34.4% increase in 2003 after several years of consecutive decrease is remarkable.
Using the figure of 16,000 t U given in [NEA 2001] for Urenco‘s tails inventory at the end of 1999, Urenco‘s related provision of EUR 112,535,000 [Urenco AR 2000] corresponds to EUR 7.03 per kg U.

In addition to transferring depleted uranium hexafluoride to Russia for re-enrichment, Urenco is exporting smaller quantities also to a number of other facilities across Europe. The figures for Urenco's German branch were disclosed by the German government‘s answer to a parliamentary question, see Table 15.

Table 14: Urenco‘s provision for liabilities and charges - Tails

Year	**Arising in year** [EUR mln]	**Released in year** [EUR mln]	**Exchange adj., etc.** [EUR mln]	**at Dec. 31** [EUR mln]	**Change**
1999				112.535	
2000	41.532	-67.501	-2.421	84.145	-25.2%
2001	48.963	-57.470	1.020	76.658	-8.9%
2002	57.382	-60.547	-2.702	70.791	-7.7%
2003	66.899	-40.146	-2.411	95.133	34.4%

Source: [Urenco AR 2000 - 2003]

Table 15: Exports of depleted uranium in the form of UF_6 from Germany to destinations other than Russia [t U]

Year	**Cogéma, Pierrelatte, France [a])**	**BNFL, Capenhurst, UK [b])**	**BNFL, Springfields, UK [c])**	**Westinghouse Atom AB, Västerås, Sweden [d])**	**TOTAL**
1998	251.188	125.645	8.504		385.337
1999	251.181	83.763			334.944
2000	100.354	66.976		17.925	185.255
2001, 1st Q.	150.570				150.570

Source: BT-Drs. 14/6692 (July 16, 2001)

[a]) presumably "Usine W" which converts depleted UF_6 to U_3O_8.

[b]) a former diffusion enrichment plant, where BNFL now operates a "uranic storage facility", where DU apparently is stored in the form of UF_6.

[c]) comprises a reconversion facility to uranium metal and a fuel production plant for uranium oxide fuel, among others.

[d]) fuel production plant for uranium oxide fuel.

The German government's answer does not contain any mention of the purpose of these exports nor the further fate of the exported DU. However, if such transfers from Urenco‘s Dutch and British plants would reach a similar order of magnitude, then these transfers could explain, why Urenco‘s DU stockpile has been on the decrease in 2001 and 2002 still, when the tails production already was larger than the tails transfers to Russia. But it becomes also clear, that with the planned further increasing capacities, Urenco will more and more run into problems to dispose of the arising tails in this „elegant“ way.

One obvious effect of the tails re-enrichment in Russia is a decrease of the amount of tails that has to be disposed of. However, the effect is only comparatively small: as a result of the re-enrichment performed on the account of Urenco and Eurodif (Step 1), the amount of tails decreases by only approx. 17%, see Table 16. As a result of the further re-enrichment performed on Rosatom‘s own account (Step 2), the amount of tails decreases by another 19% (Option N), or 8% (Option B). Overall, Russia still has to dispose of 67%, or 76%, respectively, of the amount imported.

With an assay of only 0.1%, these roughly 10,000 t U of secondary tails annually are less likely to be seen as a future resource: any attempt to recover the residual U-235 would require a tremendous separation work expenditure that cannot be expected to be affordable in the foreseeable future. Nevertheless, Rosatom still keeps these residual tails stored in the form of UF_6; it is not known what plans Rosatom has for them.

Table 16: Estimated annual tails balance for re-enrichment of imported tails in Russia

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="2">Urenco</th><th colspan="2">Eurodif</th><th>TOTAL</th></tr>
<tr><th>Tails
[t U as UF₆]</th><th>Assay</th><th>Tails
[t U as UF₆]</th><th>Assay</th><th>Tails
[t U as UF₆]</th></tr>
<tr><td colspan="2">Tails imported to Russia</td><td>7000</td><td>0.30%</td><td>7000</td><td>0.35%</td><td>14000</td></tr>
<tr><td colspan="2">Tails left after re-enrichment for Urenco / Eurodif</td><td>5906</td><td>0.224%</td><td>5766</td><td>0.21%</td><td>11672</td></tr>
<tr><td rowspan="2">Tails left after further stripping by Rosatom</td><td>Opt. N</td><td>4705</td><td rowspan="2">0.10%</td><td>4726</td><td rowspan="2">0.10%</td><td>9431</td></tr>
<tr><td>Opt. B</td><td>5382</td><td>5312</td><td>10695</td></tr>
</table>

Analysis from a uranium recovery perspective

A second important aspect of the re-enrichment deal is the recovery of residual U-235 still contained in the tails. The amounts of the recovered products are shown in Table 17.

Table 17: Estimated annual balance of recovered uranium products [t U as UF_6]
Uneq: assay 0.71%; Uenr: assay 3.5%

	Uneq			Uenr
	Urenco	**Eurodif**	**SUBTOTAL**	**Eurodif**
re-enrichment for Urenco / Eurodif	1100	1100	2200	130
further re-enrichment by Rosatom	1200	1040	2240	0
TOTAL	2300	2140	4440	130

A comparison of these figures to the current Russian annual uranium production from mines of 3150 t U (2003) shows that the total amount of „natural-equivalent“ uranium recovered by Rosatom from the imported tails is larger than Russia‘s production from mines. And, the amount of 2240 t „natural-equivalent“ uranium recovered by Rosatom from these tails on its own account adds 71% to Russia‘s uranium production from mines.

The secondary tails with an already rather low assay of 0.1% still contain residual U-235 that could be recovered at excessive expense of enrichment work only: 1328 t U/year (Option N), or 1506 t U/year (Option B) of „natural-equivalent“ uranium.
The amount of enrichment work spent by Rosatom per kg „natural-equivalent“ uranium recovered increases considerably with decreasing assay of the material fed into the re-enrichment cascade, see Table 18.

Table 18: Specific separation work for „natural-equivalent“ uranium recovered

	Uranium recovered [t Uneq/a]	**Specific separ-ation work** [SWU/kg Uneq]
Stripping from 0.30% and 0.35% to approx. 0.22% tails assay on Urenco‘s resp. Eurodif‘s account (Step 1)	2200	0.7
Further stripping to 0.1% tails assay on Rosatom‘s account (Step 2, Option N)	2240	2.1
Hypothetical further stripping to 0.05% tails assay	714	6.5

Approximately half of the „natural-equivalent“ uranium recovered on Urenco‘s and Eurodif‘s account is being supplied to European utilities (see Table 19), the other half is being sold elsewhere.

Table 19: Russian supply of re-enriched tails (of natural UF_6 equivalent) to the EU

Year	1997	1998	1999	2000	2001	2002	2003	**TOTAL**
[t U]	-	-	1100	1200	1050	1000	1200	5550

NB: For 1997 and 1998, re-enriched tails are not shown because quantities were small and could not be shown separately for confidentiality reasons.
Source: [ESA AR 2003]

Conclusions:

- For Urenco, the export to Russia represents the major disposition route for the tails currently generated in its plants.
- For several years, tails exports (mainly to Russia) resulted in a net decrease in Urenco‘s tails stocks, in spite of increasing production at Urenco‘s plants.
- The decrease in the amount of tails as a result of the re-enrichment performed is only marginal: 17% for the re-enrichment performed on Urenco‘s and Eurodif‘s account, and 33% (Opt. N) resp. 24% (Opt. B) for all re-enrichment performed on the imported tails
- The amount of 2240 t „natural-equivalent“ uranium recovered by Rosatom from the imported tails on its own account adds 71% to Russia‘s current uranium production from mines.
- The separative work expense per kg „natural-equivalent“ uranium recovered increases considerably with decreasing tails assays: the further re-enrichment performed by

Rosatom on its own account requires three times the separative work per kg recovered, compared to the re-enrichment performed on Urenco's and Eurodif's account.

' The future of the secondary tails remaining in Russia is particularly unclear, since any further extraction of residual uranium would only be possible at extreme expense of separative work.

2.3. Cost balance of the re-enrichment business

The mass balance presented above can also serve as the basis for an assessment of the economics of the re-enrichment business. However, since no hard facts are known on costs and on prices paid, some more assumptions have to be made.

Cost analysis from Urenco's and Eurodif's perspective

General assumptions:

- Urenco and Eurodif pay Rosatom for its operating cost (assumed at $20/SWU) only, and for that part of the re-enrichment only that is performed on the account of Urenco and Eurodif; Rosatom gets no extra money for the disposition of the secondary tails.
- For the determination of the reference value for the 3.5%-LEU produced for Eurodif it as assumed that natural uranium is enriched at market prices.
- for the transport cost between Urenco/Eurodif and Rosatom, a figure of $1.50 per kg UF_6 is used.

The cost balance is based on the mass balance (see above) and on various cost situations, using the market prices of three distinct dates, see Table 20.

Table 20: Cost parameters used in the cost analysis

	Uranium [$/lb U_3O_8]	**Conversion** [$/kg U]	**Enrichment** [$/SWU]	**Exchange rate** [c]) [EUR/$]
Dec. 25, 1995 [a])	12.25	5.85	95	0.74
Dec. 25, 2000 [b])	7.10	4.25	84	1.08
Nov. 15, 2004	20.25	10.00	110	0.77

[a]) this is approximately at the time the tails transfers to Russia started,

[b]) at this time, the uranium price was at its all-time low, and the enrichment price had just recovered from its lowest level.

[c]) 1995 exchange rate based on DEM/$ rate and official DEM/EUR ratio.

The annual cost balances are based on these three distinct cost situations; there is no account for any price changes occurred during the course of the year.

Four options are used for Urenco's and Eurodif's disposal cost that are being avoided by the re-enrichment:

- Option **NO**: no account for disposal cost,

- Option **US**: \$4.39 / kg U (U.S. DOE estimate for disposal as U_3O_8 in a mine),
- Option **UR**: EUR 7.03 / kg U (provision made by Urenco), and
- Option **DE**: EUR 27.24 / kg U (estimate for cemented disposal as U_3O_8 in Gorleben HLW deposit, Germany).

An overview of the resulting profit estimates for Urenco and Eurodif is given in Table 21; the detailed results are shown in the Annex: profits are generated under all market conditions examined, except for Urenco during the all-time low of the uranium price, but only without taking the avoided tails disposal cost into account

Table 21: Annual profit estimates for Urenco and Eurodif from the tails re-enrichment in Russia (\$ million)
assuming Urenco and Eurodif pay \$20/SWU for re-enrichment

	Urenco				**Eurodif**			
Disposal cost option:	**NO**	**US**	**UR**	**DE**	**NO**	**US**	**UR**	**DE**
Dec. 25, 1995	**8**	**38**	**74**	**265**	**77**	**108**	**144**	**335**
Dec. 25, 2000	-9	**22**	**37**	**168**	**38**	**69**	**84**	**215**
Nov. 15, 2004	**35**	**66**	**99**	**283**	**141**	**172**	**205**	**389**

This result is mainly based on the low SWU price of \$20/SWU presumably paid to Rosatom (just approx. one fifth of the market price). Eurodif‘s estimated profits are higher than Urenco‘s, since Eurodif‘s deal (including re-enrichment to 3.5%-LEU) requires the consumption of more SWUs; but, possibly Eurodif pays more for the SWU spent for the LEU part of its re-enrichment deal.
The result would be rather different, if Urenco and Eurodif would have to pay the market price for the re-enrichment performed by Rosatom on their behalf, see Table 22.

Table 22: Annual profit estimates for Urenco and Eurodif from the tails re-enrichment in Russia (\$ million)
assuming Urenco and Eurodif would pay market prices for re-enrichment

	Urenco				**Eurodif**			
Disposal cost option:	**NO**	**US**	**UR**	**DE**	**NO**	**US**	**UR**	**DE**
Dec. 25, 1995	-52	-21	**15**	**206**	-64	-33	**3**	**194**
Dec. 25, 2000	-59	-29	-14	**117**	-82	-52	-37	**94**
Nov. 15, 2004	-36	-5	**28**	**212**	-28	**2**	**35**	**219**

Conclusions:

- For Urenco and Eurodif, the re-enrichment deal is profitable under all market conditions examined, except for Urenco during the all-time low of the uranium price, but only without taking the avoided tails disposal cost into account.
- If Urenco and Eurodif would have to pay the market price for enrichment, the deal

would be profitable for Urenco and Eurodif only, if their avoided disposal cost were comparable to Urenco‘s provision made for tails disposition (Option UR), at least, and only if the market prices were not too low.

Cost Analysis from Rosatom‘s perspective

General assumptions:
- Rosatom gets paid for its operating cost (assumed at $20/SWU) only, and for that part of the re-enrichment only that is performed on the account of Urenco and Eurodif; Rosatom gets no extra money for the disposition of the secondary tails
- no account for any transport cost

So, if Rosatom would only perform the re-enrichment on the account for Urenco and Eurodif (Step 1), then it would make a loss as high as the disposition cost of the secondary tails.
Once Rosatom re-enriches the tails further on its own account (Step 2), the balance depends on the market prices for the products. The cost balance is analyzed for different cost situations, using the market prices for the same distinct dates as above for Urenco / Eurodif, see Table 20.

Two options are considered for the product produced by the further stripping of the tails by Rosatom on its own account:
- Option **N**: „natural-equivalent“ uranium with 0.71% assay
- Option **B**: blendstock with 1.5% assay for HEU downblending (see below)

For the determination of the reference value for the blendstock it as assumed that Unat is enriched at market prices, though this process would not yield the same low contents in U-234 (critical for blendstock use, see below).

Three options are assumed for Rosatom‘s tails disposal cost:
- Option **NO**: no account for disposal cost,
- Option **US**: $4.39 / kg U (U.S. DOE estimate for disposal as U_3O_8 in a mine),
- Option **UR**: EUR 7.03 / kg U (provision made by Urenco for its tails)

An overview of the resulting profit estimates for Rosatom is given in Table 23. The detailed results are shown in the Annex.

Table 23: Annual profit estimates for Rosatom from the tails re-enrichment ($ million) (combined data from re-enrichment of Urenco and Eurodif tails)

	Step 1 only			**Step 1 and 2**					
				Option N			**Option B**		
Disposal cost option:	**NO**	**US**	**UR**	**NO**	**US**	**UR**	**NO**	**US**	**UR**
Dec. 25, 1995	0	-51	-111	-9	-50	-99	**65**	**18**	-37
Dec. 25, 2000	0	-51	-76	-43	-84	-104	**12**	-35	-58
Nov. 15, 2004	0	-51	-107	**47**	**5**	-39	**150**	**103**	**52**

<u>Conclusions</u>:

- If Rosatom would only perform the re-enrichment on the account for Urenco and Eurodif (Step 1), then it would make a loss as high as the disposition cost of the secondary tails. So, if the assumption is correct that Urenco and Eurodif are not paying any tails disposition fee, then Rosatom has to make money by further processing of the secondary tails for not being left with its ultimate disposition cost.
- In the case that Rosatom produces uranium of natural assay in that part of the re-enrichment deal performed on its own account (Option N for Step 2), Rosatom would make a profit only at the current high market prices for uranium and enrichment services, and this only for the lower disposal cost options. In all other market conditions examined, Rosatom would suffer losses, often only slightly lower, or even higher than those experienced without any re-enrichment on its own account at all.
- If, however, Rosatom produces uranium enriched to 1.5% as blendstock for HEU downblending (Option B), then Rosatom would make profits in more cases, however, in the high disposal cost case only for the current high price level, while at the all-time low of the market prices only if no ultimate tails disposition cost are taken into account.

2.4. Blendstock production for HEU downblending

Uranium used in nuclear weapons is enriched to approx. 93% U-235, while uranium used as fuel in commercial light water reactors typically is enriched to 3 - 5% U-235. Uranium enriched to more than 20% U-235 is called Highly Enriched Uranium (HEU) and can only be used in nuclear weapons and in research reactors. Surplus HEU thus is not directly useable as fuel in nuclear power plants, but it can be downblended to Low Enriched Uranium (LEU) to make it suitable for use as commercial nuclear fuel. As blendstock material, depleted, natural, or even slightly enriched uranium can be used. <u>Table 24</u> shows a typical mass balance for HEU downblending with slightly enriched blendstock.

In 1993, the U.S. and Russia concluded the US-Russia HEU Agreement, under which Russia is supplying the downblended uranium derived from 500 t of HEU to the USA over a period of about 20 years. [UI 1999b]
The downblending is being performed at the facilities in Novouralsk, Seversk, and Zelenogorsk, by mixing the HEU and some blendstock uranium as gaseous UF_6. The LEU product obtained can be further processed in the usual way to manufacture nuclear fuel.

The problem of unwanted isotopes

The HEU material may contain several impurities, among them the unwanted uranium isotope U-234. This is a minor isotope (a member of the U-238 decay chain) contained in natural uranium; during the enrichment process, its concentration increases even more than that of U-235. High concentrations of U-234 may cause excessive worker radiation exposures during fuel fabrication.
In case natural or depleted uranium is used as blendstock, U-234 concentrations in the LEU product may exceed the ASTM specifications for nuclear fuel, shown in <u>Table 25</u>.

Table 24: Typical mass balance of HEU downblending with enriched blendstock
(per t HEU with 93% assay, 1.5% blendstock assay, 4% LEU product assay)

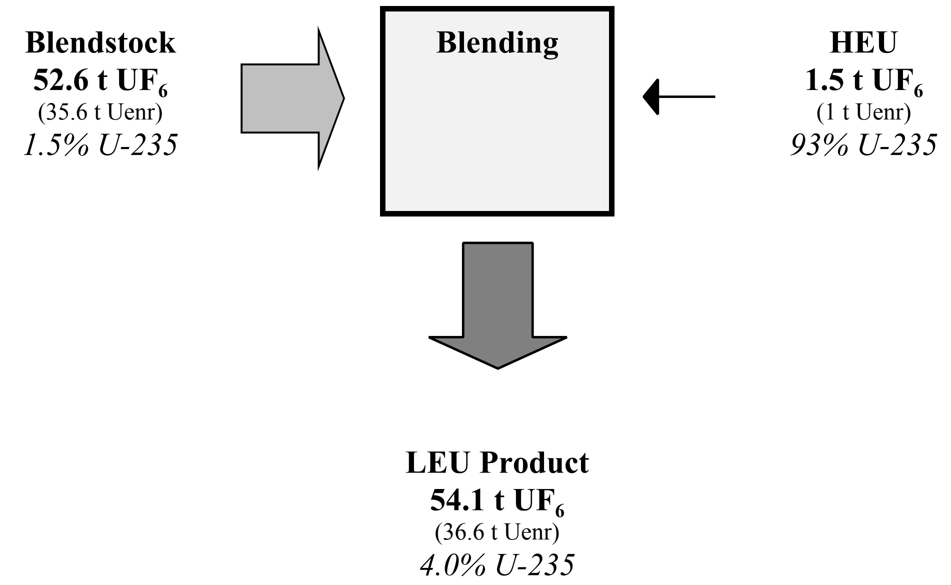


Table 25: ASTM specification C 996 for U-234 in nuclear fuel

Isotope	**max. concentration** [µg per g U-235]
U-234	10,000
	11,000 (by special agreement)

If, however, slightly enriched uranium at typically 1.5 wt-% U-235 is used as a blendstock, the unwanted isotopes are sufficiently diluted in the LEU product. The dilution effect is even stronger, if the slightly enriched blendstock is generated from re-enrichment of depleted uranium, rather than from enrichment of natural uranium. Table 26 shows the mass balance and the U-234 concentrations for various blendstock production options for the downblending of 1 t HEU. The options analyzed are:

- DU → Uenr — Tails enrichment from 0.22% to 1.5%
- Unat → Uenr — Enrichment of natural uranium to various assays
- DU → Uneq — Tails enrichment from 0.22% to 0.71%
- Unat — Direct use of natural uranium as blendstock
- Unat → DU — Use of depleted uranium (0.3%) as blendstock

From Table 26 it becomes obvious that re-enrichment of depleted uranium is not the only option to obtain downblended LEU conforming to the ASTM specification for U-234 of 10,000 µg per g U-235: enrichment of natural uranium to U-235 assays of 1.15% and higher can also generate suitable blendstock; this requires the availability of sufficient amounts of natural uranium, however.

If Rosatom uses all of the 11,672 t U of tails (at approx. 0.22% assay) left over from the re-enrichment done on behalf of Urenco and Eurodif (see Table 16 on p.17) for production of blendstock with 1.5% assay, then the resulting 1000 t U of blendstock are sufficient for the downblending of 28.1 t HEU; that is in fact the approximate annual amount to be downblended under the US-Russia HEU Agreement.

Table 26: Mass balance of blendstock production options for downblending of 1 t HEU (HEU: U-235 assay 93%, U-234 assay 1.01%; LEU: U-235 assay 4%)

<table>
<tr><th rowspan="2">Blendstock production option</th><th colspan="2">Blendstock origin</th><th colspan="3">Final Blendstock</th><th colspan="2">LEU</th></tr>
<tr><th>Mass [t U]</th><th>U-235 assay [wt-%]</th><th>Mass [t U]</th><th>U-235 assay [wt-%]</th><th>U-234 assay [wt-%]</th><th>Mass [t U]</th><th>U-234 conc. [µg/g U-235]</th></tr>
<tr><td>DU → Uenr a)</td><td>415.3</td><td>0.22%</td><td>35.6</td><td>1.50%</td><td>0.00814%</td><td>36.6</td><td>8868</td></tr>
<tr><td rowspan="3">Unat → Uenr b)</td><td>962.7</td><td rowspan="3">0.71%</td><td>130.7</td><td>3.32%</td><td>0.02803%</td><td>131.7</td><td>8867</td></tr>
<tr><td>104.2</td><td>35.6</td><td>1.50%</td><td>0.01193%</td><td>36.6</td><td>9789</td></tr>
<tr><td>64.7</td><td>31.2</td><td>1.15%</td><td>0.00897%</td><td>32.2</td><td>9994</td></tr>
<tr><td>DU → Uneq a)</td><td>137.3</td><td>0.22%</td><td>27.0</td><td>0.71%</td><td>0.00364%</td><td>28.0</td><td>9865</td></tr>
<tr><td>Unat</td><td>-</td><td>-</td><td>27.0</td><td>0.71%</td><td>0.00534%</td><td>28.0</td><td>10273</td></tr>
<tr><td>Unat → DU c)</td><td>27.4</td><td>0.71%</td><td>24.0</td><td>0.30%</td><td>0.00174%</td><td>25.0</td><td>10478</td></tr>
</table>

Note: depending on assumptions made on enrichment process details, U-234 concentrations may differ somewhat.

a) 0.1% tails assay at blendstock enrichment; blendstock origin DU generated from enrichment of Unat to 4%.

b) 0.3% tails assay at blendstock enrichment

c) blendstock DU generated from enrichment of Unat to 4%.

Recovery of separative work from the HEU

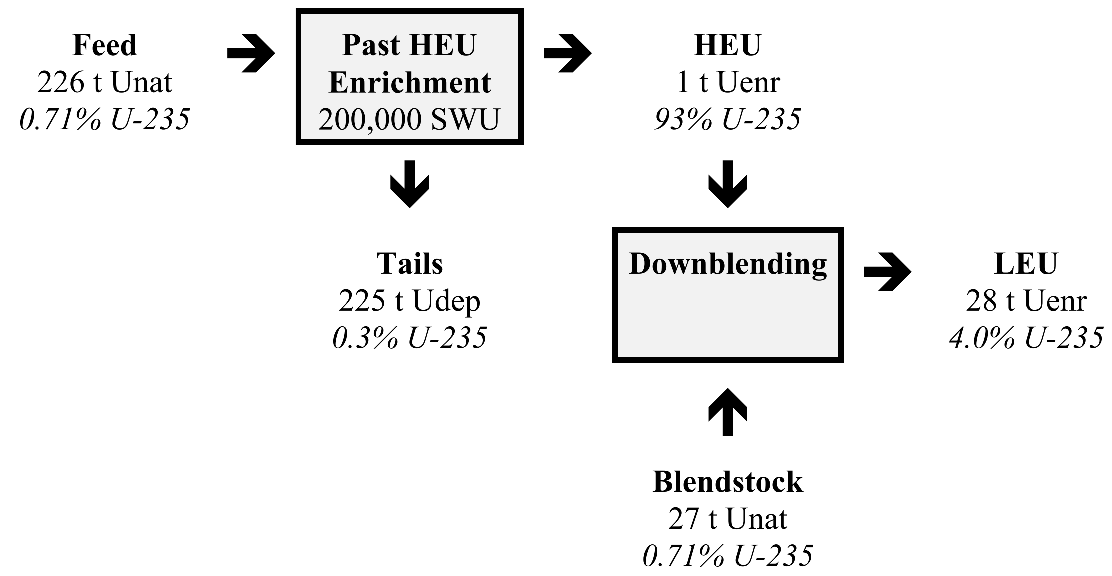
A major reason why the HEU downblending is at all performed is the recovery of the vast energy-intensive separative work spent for its production, to make it useable in nuclear fuel. Due to the nature of the downblending process, not all separative work spent for the original HEU production can be recovered, however.

With Unat as blendstock, for example, about one quarter of the SWU spent for the HEU production is lost, see Table 27: For an assessment of the usable SWU contents of the downblended LEU, a hypothetical reference case is shown, assuming direct enrichment of natural uranium to the same amount of LEU and the same assay as obtained with the LEU from downblending. If the blended LEU were produced by straight enrichment of natural uranium, then 148 SWU would have to be spent, to obtain the same amount and assay of LEU as produced from the actual downblending process per kg HEU processed. So, in the downblended LEU, we get an equivalent of 148 SWU per kg HEU blended, while the separative work originally spent for the HEU was 200 SWU per kg. Thus, 52 SWU per kg HEU, or 26% of the SWU contained in the HEU cannot be recovered and are lost.

The SWU loss increases excessively, if the separative work spent for blendstock re-enrichment from DU is taken into account. For illustration purposes, the mass balance for the currently practiced case of blendstock re-enrichment of tails from approx. 0.22% to 1.5% is presented in

detail in Table 28. Here, the reference case shows that the usable SWU contained in the LEU are 193 SWU per kg HEU blended. This is only 3.5% less than the 200 SWU per kg HEU originally spent for the production of the HEU. *But, to make those 193 SWU accessible, 232 SWU have to be spent for blendstock enrichment!* Taking the malus from blendstock enrichment into account, the corresponding net SWU loss is calculated as (200 - 193 + 232)/200 = 120%. So, in this case, the net SWU loss reaches 120% of the separative work spent for the HEU production; the *SWU loss exceeds the SWUs originally spent for the HEU by 20%*. And, in effect, other than anticipated, there is *no recovery of separative work taking place at all* in this case; the whole process is a *SWU sink*, on the contrary.
Table 29 shows the SWU loss in tabular form for the same blendstock production options as presented in Table 26.

Table 27: Estimated mass balance of HEU downblending with Unat blendstock (per t HEU)



Reference case for LEU production:

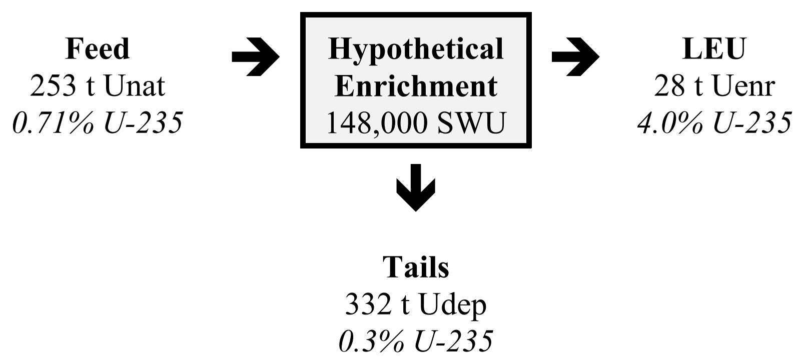
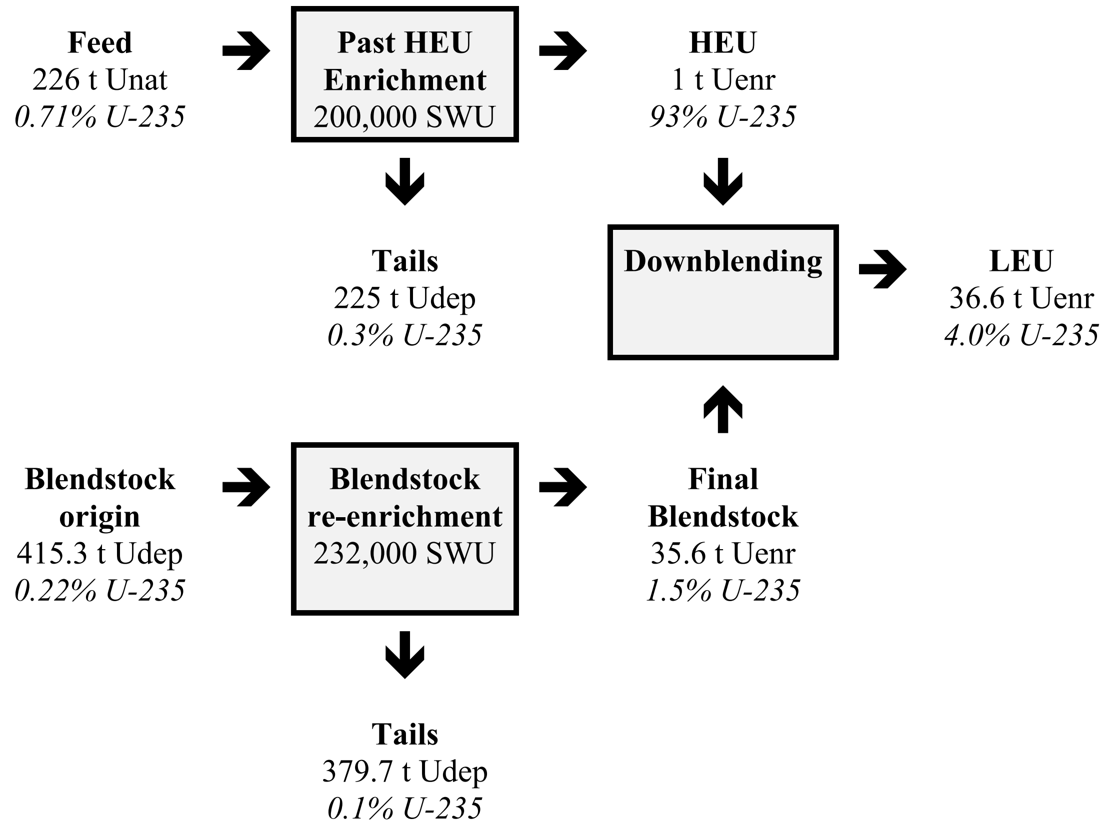


Table 28: Estimated mass balance of HEU downblending with blendstock re-enrichment (per t HEU)



Reference case for LEU production:

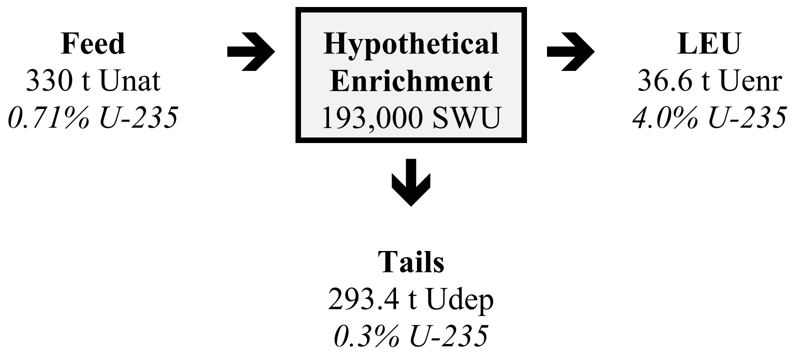


Table 29: Estimated effect of blendstock production options on SWU balance for downblending of HEU (per kg HEU)
Malus from blendstock enrichment taken into account
(200 SWU spent for enrichment of Unat to 1 kg HEU at 93% assay and 0.3% tails assay)

Blendstock production option	Blendstock origin	Final Blendstock		LEU	net SWU loss
	U-235 assay [wt-%]	U-235 assay [wt-%]	SWU spent for blendstock enrichment [SWU]	usable SWU equiv. contained [SWU]	
DU → Uenr [a])	0.22%	1.50%	232	193	**120%**
Unat → Uenr [b])	0.71%	3.32%	524	696	14%
		1.50%	33	193	20%
		1.15%	14	170	22%
DU → Uneq [a])	0.22%	0.71%	56	148	54%
Unat	-	0.71%	0	148	26%
Unat → DU [c])	0.71%	0.30%	0	132	34%

[a]) 0.1% tails assay at blendstock enrichment; blendstock origin DU generated from enrichment of Unat to 4%.
[b]) 0.3% tails assay at blendstock enrichment
[c]) blendstock DU generated from enrichment of Unat to 4%.

Recovery of the uranium feedstock component from HEU

The question, why Rosatom is spending more separative work on the feedstock enrichment than contained in and recoverable from the downblended HEU, draws the attention to the only other resource recoverable from the HEU, that is the uranium feedstock component contained.
And, indeed, a closer look shows that the downblending process presents an attractive uranium resource for Rosatom (see Table 30).

Table 30: Uranium component balance for downblending of HEU

Uranium feed originally used for HEU production, per kg HEU [a])	226 kg Unat
Uranium feed equiv. contained in downblended LEU, per kg HEU [b]) [c])	330 kg Unat
Uranium feed equiv. contained in downblend. LEU, for 28.1 t HEU [b]) [c])	9300 t Unat
excess SWU spent, per kg HEU: (20% of 200 SWU)	40 SWU
excess SWU spent per kg U feed equiv. contained in downblend. LEU	0.12 SWU/kg U

[a]) HEU: 93% product assay, enrichted from 0.71% feed assay with 0.3% tails assay
[b]) Blendstock: 1.5% assay, re-enriched from 0.22% assay tails with 0.1% secondary tails assay
[c]) LEU reference case: 4.0% product assay, enriched from 0.71% feed assay with 0.3% tails assay

If the excess separative work spent on the tails enrichment for blendstock production is attributed to the uranium feed component recovered by the downblending process, then the resulting expense of 0.12 SWU per kg U recovered is extraordinarily low (compare this to Table 18 on p.18!).

Conclusions:

- The use of re-enriched depleted uranium as blendstock is not the only option to obtain ASTM-conforming LEU from downblending of HEU. Therefore, other than it sometimes appears, re-enrichment of tails is not the sine qua non for HEU downblending.
- The combined loss of separative work from tails-enrichment for blendstock-production and from the downblending itself is 20% higher than the SWU originally spent for the HEU production. **So, in fact, the whole process consumes 20% more separative work than it can recover**. Doing nothing at all would be more efficient, from an SWU perspective, than this combination of tails-enrichment and subsequent HEU-downblending!
- The only recovery actually taking place with the current scheme of HEU downblending with re-enriched tails is the recovery of the uranium feedstock component contained in the HEU. **So, in effect, Rosatom is running an operation to recover the uranium component contained in the HEU, at the expense of quite modest separative work, while it completely sinks the tremendous separative work contained in the HEU.**
- The blendstock production therefore must be more likely seen as a reaction to the currently rather low Russian domestic uranium production from mines and Russia‘s rather limited uranium reserves mineable at current market prices, and/or as a means to circumvent existing trade restrictions for Russian SWU (see below).

2.5. Policy, trade and legal aspects of tails enrichment

Russia‘s uranium supply and demand situation

Since the dissolution of the Soviet Union, Russia is cut off from major uranium resources, mainly in Kazakhstan, see Table 31. At the current production rate of 3150 t/a (2003), Russia‘s reserves that are mineable at current uranium prices will be mined out in just 15 years.
Moreover, Russia‘s annual reactor-related uranium requirements of 5100 t U (as of 2003) exceed the domestic production by 1950 t U, or 62%. In addition, Russia has plans to build several new reactors. So, unless Russia is holding major uranium stocks (no data available), it is running into a serious uranium supply crisis in a rather short time.
On the other hand, Russia has huge surplus centrifuge enrichment capacities left over from the Cold War era (alone more than 7 million SWU are currently being used for the re-enrichment of imported tails, while further capacities are in use for re-enrichment of domestic tails). While the enrichment capacities in other countries are constantly being expanded (such as Urenco‘s plants in the UK, the Netherlands, and Germany), and old diffusion enrichment capacities are going to be replaced by centrifuge technology (such as in France and the U.S.), Russia cannot sell its surplus enrichment services on the world market, due to trade restrictions (see below).

Table 31: Uranium Resources in the former Soviet Union
Reasonably Assured Resources (RAR) as of Jan.1, 2003, vs. cost range

	< \$40/kg U ($15.38/lb U_3O_8)		**< \$80/kg U** ($30.77/lb U_3O_8)	
	[t U]	share	[t U]	share
Kazakhstan	280,620	68.4%	384,625	63.6%
Uzbekistan	61,510	15.0%	61,510	10.2%
Russia	52,610	12.8%	124,050	20.5%
Ukraine	15,380	3.8%	34,630	5.7%
TOTAL	410,120	100.0%	604,815	100.0%

Source: [NEA 2004]

So, in Russia‘s view, the second-best thing it can do with its surplus enrichment capacities is to use them to recover residual uranium from depleted uranium tails. And in fact, the estimated annual recovery of 2240 t U of „natural-equivalent“ uranium from further re-enrichment of Urenco‘s and Eurodif‘s tails on Rosatom‘s own account (see Table 17 on p.17), would already fill Russia‘s current supply gap, while Russia, in addition, is re-enriching tails from its own stocks. In Russia‘s view, the uranium recovery from the imported tails has the advantage of not using up the residual uranium „reserve“ contained in the tails stocks of its own. The total amount of uranium recovered from tails on its own account is larger than Russia‘s current needs and therefore allows for other uses, such as blendstock supply for HEU downblending.
And now it also becomes clear, why Russia is not using natural uranium for blendstock enrichment, though this would allow for the recovery of a major part of the separative work contained in the HEU: Russia simply has no surplus natural uranium available, while it disposes of vast surplus enrichment capacities.

Safeguards obligations for Australian and Canadian uranium

The major uranium producers Australia and Canada require that the depleted uranium tails remaining from enrichment or re-enrichment of uranium originating in their countries must be subject to IAEA safeguards. Russia, however, is not willing to conform to this requirement. Urenco and Eurodif, therefore, cannot send tails that were generated from enrichment of uranium originating in Australia or Canadia to Russia for re-enrichment, if the tails are to remain in Russia. Discussions are ongoing on this issue between Russia, Australia, Canada and Euratom. [UI 2001]
During the summer of 2003, a temporary arrangement was reached on tails from uranium originating in Canada; this arrangement is „limited in time, until ongoing political consultations result in a definitive solution.“ [ESA AR 2003]
The obvious option of taking the tails back apparently is not being considered, since this would undermine the economic basis for the re-enrichment in Russia.

Trade restrictions on import of Russian uranium or enrichment

The U.S. Department of Commerce (DOC) maintains a complicated system of trade restrictions on imports of Russian uranium and enrichment services, aiming at protecting its domestic uranium industry, see [UI 1999a].
The Euratom Supply Agency‘s (ESA) current policy on the import of Commonwealth of Independent States (CIS) uranium and Russian enrichment seeks to maintain diversity of sources. This means that EU utilities (i.e. the end-users) should not depend, on average, for more than about one quarter of their natural uranium needs on CIS suppliers; for Russian enrichment the limit is slightly less than one fifth of their needs. ESA‘s policy moreover aims at assuring „market-related“ prices. [UI 2000]

Trade restrictions on import of tails re-enriched in Russia

The United States considers that re-enriched tails material is subject to the same import restrictions as Russian material. Among other restrictions, it is subject to the provisions of the US-Russia Suspension Agreement and the USEC Privatization Act. [UI 2001] [UI 1999a]
The Euratom Supply Agency considers re-enriched tails material, if sold in the form in which it is imported, as Russian and subject to the same limitations as those applicable to other uranium imports from countries in the CIS. *However, if the material is further enriched within the EU then it is not subject to such limitations and can be sold to EU end-users without restriction*. [UI 2001] [UI 2000]

Legal aspect: import of radioactive waste?

The secondary tails generated during the upgrading process remain in Russia. Considering that the re-enrichment process results only in a minor reduction of the amount of tails to be disposed of, the possibility must be taken into consideration that the tails transfer to Russia constitutes an illegal transfer of radioactive waste for final disposal.
Given the various uses Russia is making of the recovered uranium, this view might appear somewhat inappropriate; but it has to be kept in mind that all this re-enrichment is only being performed, since Russia apparently is doing it for the operating cost only (presumably 18% of the current market price). If the re-enrichment were so economically attractive, then Urenco and Eurodif would do it on their own. And, if the residual uranium contained in the tails were so valuable, then Urenco and Eurodif would be eager to keep the tails rather than to give them away on the contrary, as is the case now.
For Urenco and Eurodif, the main purpose of the deal is to "solve" their waste management problem by transferring the depleted uranium to Russia.
The German Federal Government, however, stresses the results of an investigation it has conducted together with the governments of the United Kingdom and the Netherlands. The study has approved that the re-enrichment in Russia is „not connected to a management of residues violating international rules, standards, or obligations“. [BT-Drs.13/8810, Oct. 22, 1997]

Conclusions:

- Russia faces a serious shortage in uranium supply from domestic ore deposits, while it has huge surplus uranium enrichment capacities.
- Trade restrictions limit the sale of surplus Russian separative work, except when uranium recovered in Russia from imported tails is further enriched in the EU.
- The re-enrichment of imported tails gives Russia access to additional uranium resources at the expense of separative work, and it gives Russia the occasion to sell part of its SWU, though not at market prices.
- The fact that the ultimate tails, comprising roughly 10,000 t U (contained in 15,000 t of UF_6) annually, remain in Russia with unknown fate gives rise to the suspicion that the tails import constitutes an illegal transfer of nuclear waste. This view is supported by the fact that the re-enrichment reduces the amount of the tails only by a minor fraction, and by the very low likeliness that the residual uranium still contained in the ultimate tails may ever be recoverable economically, and by taking into account that the whole re-enrichment business is only functioning at prices that are a small fraction of market prices.

Depleted uranium storage cylinders at the Portsmouth (Ohio) Gaseous Diffusion Plant site. (U.S. DOE)

Annex: Mass- and cost balance

Option N

Product produced by Rosatom by further stripping of the secondary tails on its own account is **natural-equivalent uranium** with 0.71% assay.

Table columns:

- **Urenco**: re-enrichment of Urenco tails to natural-equivalent assay
- **Ed. (neq)**: re-enrichment of one part of Eurodif tails to natural-equivalent assay
- **Ed. (enr)**: re-enrichment of other part of Eurodif tails to 3.5% assay
- **Ed. (tot)**: total for re-enrichment of all Eurodif tails
- **Ure.+Ed.**: total for re-enrichment of Urenco and Eurodif tails
- **Ref.case**: reference case for enrichment to 3.5% (to determine product value)

Assumptions for Mass Balance:

- Conversion losses not included,
- Depleted and natural UF_6 transported in 48Y cylinders,
- Enriched UF_6 transported in 30B cylinders,
- Re-enrichment divided in 2 subsequent steps (for accounting purposes), though physically one process:
  - Step 1: performed by Rosatom on the account of Urenco and Eurodif
  - Step 2: performed by Rosatom on its own account, 0.71% assay (natural-equivalent)

Assumptions for Cost Balances:

- Urenco and Eurodif pay operating cost price for re-enrichment Step 1 only,
- Three options for avoided tails disposal cost for Urenco and Eurodif:
  - **US**: U.S. DOE estimate for cemented disposal as U_3O_8 in a mine,
  - **UR**: provision made by Urenco, and
  - **DE**: estimate for cemented disposal as U_3O_8 in Gorleben HLW deposit, Germany.
- Two options for tails disposal cost for Rosatom: **US** and **UR** (as above)
- For the value of the natural-equivalent uranium and enriched uranium obtained, the market price for uranium of the respective assays is used.
- Prices are spot market prices for the dates given, as obtained from Ux Consulting Company, LLC, http://www.uxc.com ; no account for price changes during the year.
- Exchange rates are as obtained from „The Currency Site“ http://www.oanda.com/ (for dates before the introduction of the Euro, the DEM exchange rate was used and converted to EUR using the official DEM/EUR ratio of 1.95583)

Conventions:

t stands for metric tonne, % stands for weight-percent, $ stands for US-Dollar
Uneq: „natural-equivalent“ uranium (0.71% assay)
profit UE: profit for Urenco / Eurodif
profit R: profit for Rosatom

ANNUAL MASS BALANCE - OPT. N	Urenco	Ed. (neq)	Ed. (enr)	Ed. tot	Ure.+Ed.	Ref. Case
Constants						
mass ratio U/UF6	0.676	0.676	0.676			0.676
mass ratio U/U3O8	0.848	0.848	0.848			
lb U3O8 / kg U	2.600	2.600	2.600			
capacity of 48Y cylinder [t UF6]	12.501	12.501	12.501			
capacity of 30B cylinder [t UF6]			2.277			
Urenco/Eurodif enrichment						
feed assay [% U235]	0.71	0.71	0.71			
product assay [% U235]	3.60	3.60	3.60			
tails assay [% U235]	0.30	0.35	0.35			
feed quantity Unat in UF6 [t U]	7993.08	4436.00	3435.97	7871.97	15865.05	
feed quantity UF6 [t UF6]	11820.81	6560.32	5081.39	11641.71	23462.52	
product quantity UF6 [t UF6]	1468.65	726.68	562.86	1289.54	2758.19	
product quantity U in UF6 [t U]	993.08	491.37	380.60	871.97	1865.05	
tails quantity UF6 [t UF6]	10352.17	5833.63	4518.53	10352.16	20704.33	
tails quantity U in UF6 [t U]	7000.00	3944.63	3055.37	7000.00	14000.00	
number of 48Y cylinders for tails	829	467	362	829	1658	
separation work [million SWU]	4.50	2.03	1.57	3.60	8.10	
Tails upgrading Step 1						
feed assay [% U235]	0.30	0.35	0.35			0.71
product assay [% U235]	0.71	0.71	3.50			3.50
tails assay [% U235]	0.224	0.21	0.21			0.35
feed quantity UF6 [t UF6]	10352.17	5833.63	4518.53	10352.16	20704.33	1682.20
feed quantity U in UF6 [t U]	7000.00	3944.63	3055.37	7000.00	14000.00	1137.48
product quantity [t UF6]	1618.86	1633.42	192.28			192.25
product quantity U in UF6 [t U]	1094.65	1104.50	130.02			130.00
number of 48Y cylinders for product Uneq	130	131		131	261	
number of 30B cylinders for product Uenr			85	85	85	
tails quantity [t UF6]	8733.31	4200.22	4326.25	8526.47	17259.78	1489.95
tails quantity U in UF6 [t U]	5905.35	2840.13	2925.35	5765.49	11670.84	1007.48
separation work [million SWU]	0.79	0.67	1.21	1.88	2.67	0.51
Tails upgrading Step 2						
feed assay [% U235]	0.224	0.21	0.21			
product assay [% U235]	0.71	0.71	0.71			
tails assay [% U235]	0.10	0.10	0.10			
feed quantity UF6 [t UF6]	8733.31	4200.22	4326.25	8526.47	17259.78	
feed quantity U in UF6 [t U]	5905.35	2840.13	2925.35	5765.49	11670.84	
product quantity [t UF6]	1775.30	757.42	780.14	1537.56	3312.86	
product quantity U in UF6 [t U]	1200.43	512.15	527.52	1039.68	2240.11	
tails quantity [t UF6]	6958.01	3442.80	3546.11	6988.91	13946.92	
tails quantity U in UF6 [t U]	4704.92	2327.98	2397.83	4725.81	9430.73	
number of 48Y cylinders for tails	557	276	284	560	1117	
residual Uneq equiv. contained in tails [t U]	662.66	327.88	337.72	665.61	1328.27	
separation work [million SWU]	2.42	1.11	1.14	2.25	4.67	

SPECIFIC TAILS DISPOSAL COST	Urenco	Ed. (neq)	Ed. (enr)	Ed. tot	Ure.+Ed.	Ref. Case
Specific Tails Disposal Cost (DE)						
specific deconversion cost UF6 to U3O8 [EUR/kg UF6]	1.60					
specific deconversion cost UF6 to U3O8 [EUR/kg U]	2.37					
cost for storage of 200-litre barrel [EUR]	7670.00					
specific storage cost per litre [EUR/ltr]	38.35					
specific storage volume per t U3O8 [ltr/t U3O8]	550.00					
specific storage cost per kg U3O8 [EUR/kg U3O8]	21.09					
specific storage cost per kg U as U3O8 [EUR/kg U]	24.87					
specif. storage cost per kg UF6 as U3O8 [EUR/kg UF6]	16.82					
specific disposal cost (deconv. + storage) [EUR/kg U]	27.24	27.24	27.24			
- as above for UF6 [EUR/kg UF6]	18.42	18.42	18.42			
Specific Tails Disposal Cost (UR)						
specific disposal cost (deconv. + storage) [EUR/kg U]	7.03	7.03	7.03			
- as above for UF6 [EUR/kg UF6]	4.75	4.75	4.75			
Specific Tails Disposal Cost (US)						
specific deconversion cost UF6 to U3O8 [$/kg UF6]	0.48					
specific storage cost per kg UF6 as U3O8 [$/kg UF6]	2.49					
specific disposal cost (deconv. + storage) [$/kg UF6]	2.97	2.97	2.97			
- as above for U [$/kg U]	4.39	4.39	4.39			

ANNUAL COST BALANCE - OPT.N, Dec.25, 1995	**Urenco**	**Ed. (neq)**	**Ed. (enr)**	**Ed. tot**	**Ure.+Ed.**	**Ref. Case**
General cost data						
price of Unat [$/lb U3O8]	12.25	12.25	12.25			
price of Unat as U3O8 [$/kg U]	31.85	31.85	31.85			
specific conversion cost U3O8 to UF6 [$/kg U]	5.85	5.85	5.85			
price of Unat as UF6 [$/kg U]	37.70	37.70	37.70			37.70
exchange rate [EUR/$]	0.74	0.74	0.74			
Urenco/Eurodif enrichment plant						
theoretical tails disposal cost (DE) [$ million]	257.67	145.20	112.47	257.67	515.34	
theoretical tails disposal cost (UR) [$ million]	66.50	37.47	29.03	66.50	133.00	
theoretical tails disposal cost (US) [$ million]	30.75	17.33	13.42	30.75	61.49	
Tails upgrading Step 1						
specific transport cost [$/kg UF6]	1.50	1.50	1.50			
transport cost [$ million]	17.96	11.20	7.07	18.27	36.22	
specific separation work cost [$/SWU]	20.00	20.00	20.00			95.00
separation work cost [$ million]	15.76	13.49	24.20	37.69	53.45	48.92
separation work cost per kg Uneq produced [$/kg U]	14.39	12.22				
separation work cost per t UF6 feed [$/t UF6]	1522.08	2312.79	5355.10			
price paid for re-enrichment [$ million]	15.76	13.49	24.20			
market value of the product as UF6 [$ million]	41.27	41.64	91.80	133.44	174.71	91.80
theoretical tails disposal cost (UR) [$ million]	56.10	26.98	27.79	54.77	110.87	
theoretical tails disposal cost (US) [$ million]	25.94	12.47	12.85	25.32	51.26	
profit UE1NO = prod. val. ./. transp ./. sep. [$ million]	7.56	16.95	60.54	77.49	85.04	
profit UE1DE = UE1NO + avoid.disp. (DE) [$ million]	265.22	162.15	173.01	335.16	600.38	
profit UE1UR = UE1NO + avoid.disp. (UR) [$ million]	74.06	54.42	89.57	143.99	218.04	
profit UE1US = UE1NO + avoid.disp. (US) [$ million]	38.30	34.27	73.96	108.23	146.53	
profit R1UR = re-e.pr. ./. sep. ./. disp.(UR) [$ million]	-56.10	-26.98	-27.79	-54.77	-110.87	
profit R1US = re-e.pr. ./. sep. ./. disp.(US) [$ million]	-25.94	-12.47	-12.85	-25.32	-51.26	
Tails upgrading Step 2						
specific separation work cost [$/SWU]	20.00	20.00	20.00			
separation work cost [$ million]	48.43	22.18	22.84	45.02	93.45	
separation work cost per kg Uneq produced [$/kg U]	40.35	43.30	43.30	43.30	41.72	
separation work cost per t UF6 feed [$/t UF6]	5545.87	5279.52	5279.52	5279.52	5414.29	
market value of the product Uneq as UF6 [$ million]	45.26	19.31	19.89	39.20	84.45	
tails disposal cost (UR) [$ million]	44.70	22.12	22.78	44.90	89.59	
tails disposal cost (US) [$ million]	20.67	10.23	10.53	20.76	41.42	
profit R2NO = R1 + prod. val. + avoid.disp. ./. separ. [$ million]	-3.18	-2.87	-2.95	-5.82	-9.00	
profit R2UR = R2NO ./. disp. cost (UR) [$ million]	-47.87	-24.98	-25.73	-50.72	-98.59	
profit R2US = R2NO ./. disp. cost (US) [$ million]	-23.84	-13.09	-13.48	-26.58	-50.42	

ANNUAL COST BALANCE - OPT.N, Dec.25, 2000	**Urenco**	**Ed. (neq)**	**Ed. (enr)**	**Ed. tot**	**Ure.+Ed.**	**Ref. Case**
General cost data						
price of Unat [$/lb U3O8]	7.10	7.10	7.10			
price of Unat as U3O8 [$/kg U]	18.46	18.46	18.46			
specific conversion cost U3O8 to UF6 [$/kg U]	4.25	4.25	4.25			
price of Unat as UF6 [$/kg U]	22.71	22.71	22.71			22.71
exchange rate [EUR/$]	1.08	1.08	1.08			
Urenco/Eurodif enrichment plant						
theoretical tails disposal cost (DE) [$ million]	176.55	99.49	77.06	176.55	353.10	
theoretical tails disposal cost (UR) [$ million]	45.56	25.68	19.89	45.56	91.13	
theoretical tails disposal cost (US) [$ million]	30.75	17.33	13.42	30.75	61.49	
Tails upgrading Step 1						
specific transport cost [$/kg UF6]	1.50	1.50	1.50			
transport cost [$ million]	17.96	11.20	7.07	18.27	36.22	
specific separation work cost [$/SWU]	20.00	20.00	20.00			84.00
separation work cost [$ million]	15.76	13.49	24.20	37.69	53.45	43.26
separation work cost per kg Uneq produced [$/kg U]	14.39	12.22				
separation work cost per t UF6 feed [$/t UF6]	1522.08	2312.79	5355.10			
price paid for re-enrichment [$ million]	15.76	13.49	24.20			
market value of the product as UF6 [$ million]	24.86	25.08	69.09	94.17	119.03	69.09
theoretical tails disposal cost (UR) [$ million]	38.44	18.49	19.04	37.53	75.97	
theoretical tails disposal cost (US) [$ million]	25.94	12.47	12.85	25.32	51.26	
profit UE1NO = prod. val. ./. transp ./. sep. [$ million]	-8.85	0.39	37.82	38.22	29.36	
profit UE1DE = UE1NO + avoid.disp. (DE) [$ million]	167.70	99.88	114.89	214.77	382.46	
profit UE1UR = UE1NO + avoid.disp. (UR) [$ million]	36.71	26.07	57.71	83.78	120.49	
profit UE1US = UE1NO + avoid.disp. (US) [$ million]	21.89	17.72	51.24	68.96	90.85	
profit R1UR = re-e.pr. ./. sep. ./. disp.(UR) [$ million]	-38.44	-18.49	-19.04	-37.53	-75.97	
profit R1US = re-e.pr. ./. sep. ./. disp.(US) [$ million]	-25.94	-12.47	-12.85	-25.32	-51.26	
Tails upgrading Step 2						
specific separation work cost [$/SWU]	20.00	20.00	20.00			
separation work cost [$ million]	48.43	22.18	22.84	45.02	93.45	
separation work cost per kg Uneq produced [$/kg U]	40.35	43.30	43.30	43.30	41.72	
separation work cost per t UF6 feed [$/t UF6]	5545.87	5279.52	5279.52	5279.52	5414.29	
market value of the product Uneq as UF6 [$ million]	27.26	11.63	11.98	23.61	50.87	
tails disposal cost (UR) [$ million]	30.63	15.15	15.61	30.76	61.39	
tails disposal cost (US) [$ million]	20.67	10.23	10.53	20.76	41.42	
profit R2NO = R1 + prod. val. + avoid.disp. ./. separ. [$ million]	-21.17	-10.54	-10.86	-21.40	-42.58	
profit R2UR = R2NO ./. disp. cost (UR) [$ million]	-51.80	-25.70	-26.47	-52.17	-103.96	
profit R2US = R2NO ./. disp. cost (US) [$ million]	-41.84	-20.77	-21.39	-42.16	-84.00	

ANNUAL COST BALANCE - OPT.N, Nov. 15, 2004	**Urenco**	**Ed. (neq)**	**Ed. (enr)**	**Ed. tot**	**Ure.+Ed.**	**Ref. Case**
General cost data						
price of Unat [$/lb U3O8]	20.25	20.25	20.25			
price of Unat as U3O8 [$/kg U]	52.65	52.65	52.65			
specific conversion cost U3O8 to UF6 [$/kg U]	10.00	10.00	10.00			
price of Unat as UF6 [$/kg U]	62.65	62.65	62.65			62.65
exchange rate [EUR/$]	0.77	0.77	0.77			
Urenco/Eurodif enrichment plant						
theoretical tails disposal cost (DE) [$ million]	247.63	139.54	108.09	247.63	495.26	
theoretical tails disposal cost (UR) [$ million]	63.91	36.01	27.90	63.91	127.82	
theoretical tails disposal cost (US) [$ million]	30.75	17.33	13.42	30.75	61.49	
Tails upgrading Step 1						
specific transport cost [$/kg UF6]	1.50	1.50	1.50			
transport cost [$ million]	17.96	11.20	7.07	18.27	36.22	
specific separation work cost [$/SWU]	20.00	20.00	20.00			110.00
separation work cost [$ million]	15.76	13.49	24.20	37.69	53.45	56.64
separation work cost per kg Uneq produced [$/kg U]	14.39	12.22				
separation work cost per t UF6 feed [$/t UF6]	1522.08	2312.79	5355.10			
price paid for re-enrichment [$ million]	15.76	13.49	24.20			
market value of the product as UF6 [$ million]	68.58	69.20	127.91	197.10	265.68	127.91
theoretical tails disposal cost (UR) [$ million]	53.92	25.93	26.71	52.64	106.55	
theoretical tails disposal cost (US) [$ million]	25.94	12.47	12.85	25.32	51.26	
profit UE1NO = prod. val. ./. transp ./. sep. [$ million]	34.87	44.50	96.64	141.15	176.01	
profit UE1DE = UE1NO + avoid.disp. (DE) [$ million]	282.50	184.05	204.73	388.78	671.27	
profit UE1UR = UE1NO + avoid.disp. (UR) [$ million]	98.78	80.52	124.54	205.06	303.83	
profit UE1US = UE1NO + avoid.disp. (US) [$ million]	65.61	61.83	110.06	171.89	237.51	
profit R1UR = re-e.pr. ./. sep. ./. disp.(UR) [$ million]	-53.92	-25.93	-26.71	-52.64	-106.55	
profit R1US = re-e.pr. ./. sep. ./. disp.(US) [$ million]	-25.94	-12.47	-12.85	-25.32	-51.26	
Tails upgrading Step 2						
specific separation work cost [$/SWU]	20.00	20.00	20.00			
separation work cost [$ million]	48.43	22.18	22.84	45.02	93.45	
separation work cost per kg Uneq produced [$/kg U]	40.35	43.30	43.30	43.30	41.72	
separation work cost per t UF6 feed [$/t UF6]	5545.87	5279.52	5279.52	5279.52	5414.29	
market value of the product Uneq as UF6 [$ million]	75.21	32.09	33.05	65.14	140.34	
tails disposal cost (UR) [$ million]	42.96	21.25	21.89	43.15	86.10	
tails disposal cost (US) [$ million]	20.67	10.23	10.53	20.76	41.42	
profit R2NO = R1 + prod. val. + avoid.disp. ./. separ. [$ million]	26.77	9.91	10.21	20.12	46.89	
profit R2UR = R2NO ./. disp. cost (UR) [$ million]	-16.18	-11.34	-11.68	-23.03	-39.21	
profit R2US = R2NO ./. disp. cost (US) [$ million]	6.11	-0.31	-0.32	-0.64	5.47	

Option B

Product produced by Rosatom by further stripping of the secondary tails on its own account is **blendstock uranium** with 1.5% assay for use in HEU downblending.

Table columns:

- **Urenco**: re-enrichment of Urenco tails to natural-equivalent assay
- **Ed. (neq)**: re-enrichment of one part of Eurodif tails to natural-equivalent assay
- **Ed. (enr)**: re-enrichment of other part of Eurodif tails to 3.5% assay
- **Ed. (tot)**: total for re-enrichment of all Eurodif tails
- **Ure.+Ed.**: total for re-enrichment of Urenco and Eurodif tails
- **Ref.case**: reference cases for enrichment to 3.5% and 1.5% (to determine product value)

Assumptions for Mass Balance:

- Conversion losses not included,
- Depleted and natural UF_6 transported in 48Y cylinders,
- Enriched UF_6 transported in 30B cylinders,
- Re-enrichment divided in 2 subsequent steps (for accounting purposes), though physically one process:
  - Step 1: performed by Rosatom on the account of Urenco and Eurodif
  - Step 2: performed by Rosatom on its own account, 1.5% assay for blendstock

Assumptions for Cost Balances:

- Urenco and Eurodif pay operating cost price for re-enrichment Step 1 only,
- Three options for avoided tails disposal cost for Urenco and Eurodif:
  - **US**: U.S. DOE estimate for cemented disposal as U_3O_8 in a mine,
  - **UR**: equivalent to provision made by Urenco, and
  - **DE**: estimate for cemented disposal as U_3O_8 in Gorleben HLW deposit, Germany.
- Two options for tails disposal cost for Rosatom: **US** and **UR** (as above)
- For the value of the natural-equivalent uranium, enriched uranium, and blendstock uranium obtained, the market price for uranium of the respective assays is used.
- Prices are spot market prices for the dates given, as obtained from Ux Consulting Company, LLC, http://www.uxc.com ; no account for price changes during the year.
- Exchange rates are as obtained from „The Currency Site“ http://www.oanda.com/ (for dates before the introduction of the Euro, the DEM exchange rate was used and converted to EUR using the official DEM/EUR ratio of 1.95583)

Conventions:

t stands for metric tonne, % stands for weight-percent, $ stands for US-Dollar
Uneq: „natural-equivalent“ uranium (0.71% assay)
profit UE: profit for Urenco / Eurodif
profit R: profit for Rosatom

ANNUAL MASS BALANCE - OPT. B	Urenco	Ed. (neq)	Ed. (enr)	Ed. tot	Ure.+Ed.	Ref. Case
Constants						
mass ratio U/UF6	0.676	0.676	0.676			0.676
mass ratio U/U3O8	0.848	0.848	0.848			
lb U3O8 / kg U	2.600	2.600	2.600			
capacity of 48Y cylinder [t UF6]	12.501	12.501	12.501			
capacity of 30B cylinder [t UF6]			2.277			2.277
Urenco/Eurodif enrichment						
feed assay [% U235]	0.71	0.71	0.71			
product assay [% U235]	3.60	3.60	3.60			
tails assay [% U235]	0.30	0.35	0.35			
feed quantity Unat in UF6 [t U]	7993.08	4436.00	3435.97	7871.97	15865.05	
feed quantity UF6 [t UF6]	11820.81	6560.32	5081.39	11641.71	23462.52	
product quantity UF6 [t UF6]	1468.65	726.68	562.86	1289.54	2758.19	
product quantity U in UF6 [t U]	993.08	491.37	380.60	871.97	1865.05	
tails quantity UF6 [t UF6]	10352.17	5833.63	4518.53	10352.16	20704.33	
tails quantity U in UF6 [t U]	7000.00	3944.63	3055.37	7000.00	14000.00	
number of 48Y cylinders for tails	829	467	362	829	1658	
separation work [million SWU]	4.50	2.03	1.57	3.60	8.10	
Tails upgrading Step 1						
feed assay [% U235]	0.30	0.35	0.35			0.71
product assay [% U235]	0.71	0.71	3.50			3.50
tails assay [% U235]	0.224	0.21	0.21			0.35
feed quantity UF6 [t UF6]	10352.17	5833.63	4518.53	10352.16	20704.33	1682.00
feed quantity U in UF6 [t U]	7000.00	3944.63	3055.37	7000.00	14000.00	1137.35
product quantity [t UF6]	1618.86	1633.42	192.28			192.23
product quantity U in UF6 [t U]	1094.65	1104.50	130.02			129.98
number of 48Y cylinders for product Uneq	130	131		131	261	
number of 30B cylinders for product Uenr			85	85	85	85
tails quantity [t UF6]	8733.31	4200.22	4326.25	8526.47	17259.78	1489.77
tails quantity U in UF6 [t U]	5905.35	2840.13	2925.35	5765.49	11670.84	1007.36
separation work [million SWU]	0.79	0.67	1.21	1.88	2.67	0.51
Tails upgrading Step 2						
feed assay [% U235]	0.224	0.21	0.21			0.71
product assay [% U235]	1.50	1.50	1.50			1.50
tails assay [% U235]	0.10	0.10	0.10			0.30
feed quantity UF6 [t UF6]	8733.31	4200.22	4326.25	8526.47	17259.78	4224.75
feed quantity U in UF6 [t U]	5905.35	2840.13	2925.35	5765.49	11670.84	2856.72
product quantity [t UF6]	773.52	330.02	339.92	669.94	1443.46	1443.46
product quantity U in UF6 [t U]	523.05	223.15	229.85	453.00	976.05	976.05
tails quantity [t UF6]	7959.79	3870.20	3986.33	7856.53	15816.32	2781.29
tails quantity U in UF6 [t U]	5382.30	2616.98	2695.51	5312.48	10694.79	1880.67
number of 48Y cylinders for tails	637	310	319	629	1266	
residual Uneq equiv. contained in tails [t U]	758.07	368.59	379.65	748.24	1506.31	794.65
separation work [million SWU]	3.37	1.51	1.56	3.07	6.44	0.90

SPECIFIC TAILS DISPOSAL COST	Urenco	Ed. (neq)	Ed. (enr)	Ed. tot	Ure.+Ed.	Ref. Case
Specific Tails Disposal Cost (DE)						
specific deconversion cost UF6 to U3O8 [EUR/kg UF6]	1.60					
specific deconversion cost UF6 to U3O8 [EUR/kg U]	2.37					
cost for storage of 200-litre barrel [EUR]	7670.00					
specific storage cost per litre [EUR/ltr]	38.35					
specific storage volume per t U3O8 [ltr/t U3O8]	550.00					
specific storage cost per kg U3O8 [EUR/kg U3O8]	21.09					
specific storage cost per kg U as U3O8 [EUR/kg U]	24.87					
specif. storage cost per kg UF6 as U3O8 [EUR/kg UF6]	16.82					
specific disposal cost (deconv. + storage) [EUR/kg U]	27.24	27.24	27.24			
- as above for UF6 [EUR/kg UF6]	18.42	18.42	18.42			
Specific Tails Disposal Cost (UR)						
specific disposal cost (deconv. + storage) [EUR/kg U]	7.03	7.03	7.03			
- as above for UF6 [EUR/kg UF6]	4.75	4.75	4.75			
Specific Tails Disposal Cost (US)						
specific deconversion cost UF6 to U3O8 [$/kg UF6]	0.48					
specific storage cost per kg UF6 as U3O8 [$/kg UF6]	2.49					
specific disposal cost (deconv. + storage) [$/kg UF6]	2.97	2.97	2.97			
- as above for U [$/kg U]	4.39	4.39	4.39			

ANNUAL COST BALANCE - OPT.B, Dec. 25, 1995	**Urenco**	**Ed. (neq)**	**Ed. (enr)**	**Ed. tot**	**Ure.+Ed.**	**Ref. Case**
General cost data						
price of Unat [$/lb U3O8]	12.25	12.25	12.25			
price of Unat as U3O8 [$/kg U]	31.85	31.85	31.85			
specific conversion cost U3O8 to UF6 [$/kg U]	5.85	5.85	5.85			
price of Unat as UF6 [$/kg U]	37.70	37.70	37.70			37.70
exchange rate [EUR/$]	0.74	0.74	0.74			
Urenco/Eurodif enrichment plant						
theoretical tails disposal cost (DE) [$ million]	257.67	145.20	112.47	257.67	515.34	
theoretical tails disposal cost (UR) [$ million]	66.50	37.47	29.03	66.50	133.00	
theoretical tails disposal cost (US) [$ million]	30.75	17.33	13.42	30.75	61.49	
Tails upgrading Step 1						
specific transport cost [$/kg UF6]	1.50	1.50	1.50			
transport cost [$ million]	17.96	11.20	7.07	18.27	36.22	
specific separation work cost [$/SWU]	20.00	20.00	20.00			95.00
separation work cost [$ million]	15.76	13.49	24.20	37.69	53.45	48.91
separation work cost per kg Uneq produced [$/kg U]	14.39	12.22				
separation work cost per t UF6 feed [$/t UF6]	1522.08	2312.79	5355.10			
price paid for re-enrichment [$ million]	15.76	13.49	24.20			
market value of the product as UF6 [$ million]	41.27	41.64	91.79	133.43	174.70	91.79
theoretical tails disposal cost (UR) [$ million]	56.10	26.98	27.79	54.77	110.87	
theoretical tails disposal cost (US) [$ million]	25.94	12.47	12.85	25.32	51.26	
profit UE1NO = prod. val. ./. transp. ./. sep. [$ million]	7.56	16.95	60.53	77.48	85.03	
profit UE1DE = UE1NO + avoid.disp. (DE) [$ million]	265.22	162.15	173.00	335.14	600.37	
profit UE1UR = UE1NO +avoid.disp. (UR) [$ million]	74.06	54.42	89.55	143.98	218.03	
profit UE1US = UE1NO + avoid.disp. (US) [$ million]	38.30	34.27	73.95	108.22	146.52	
profit R1UR = re-e.pr. ./. sep. ./. disp.(UR) [$ million]	-56.10	-26.98	-27.79	-54.77	-110.87	
profit R1US = re-e.pr. ./. sep. ./. disp.(US) [$ million]	-25.94	-12.47	-12.85	-25.32	-51.26	
Tails upgrading Step 2						
specific separation work cost [$/SWU]	20.00	20.00	20.00			95.00
separation work cost [$ million]	67.35	30.24	31.15	61.40	128.74	85.73
separation work cost per kg Uenr produced [$/kg U]	128.76	135.53	135.53	135.53	131.90	
separation work cost per t UF6 feed [$/t UF6]	7711.60	7200.72	7200.72	7200.72	7459.22	
market value of the product Uenr as UF6 [$ million]	103.66	44.22	45.55	89.78	193.43	193.43
tails disposal cost (UR) [$ million]	51.13	24.86	25.61	50.47	101.60	
tails disposal cost (US) [$ million]	23.64	11.49	11.84	23.33	46.97	
profit R2NO = R1 + prod. val. + avoid.disp. ./. separ. [$ million]	36.31	13.98	14.40	28.38	64.69	
profit R2UR = R2NO ./. disp. cost (UR) [$ million]	-14.82	-10.88	-11.21	-22.09	-36.91	
profit R2US = R2NO ./. disp. cost (US) [$ million]	12.67	2.48	2.56	5.04	17.71	

ANNUAL COST BALANCE - OPT.B, Dec. 25, 2000	**Urenco**	**Ed. (neq)**	**Ed. (enr)**	**Ed. tot**	**Ure.+Ed.**	**Ref. Case**
General cost data						
price of Unat [$/lb U3O8]	7.10	7.10	7.10			
price of Unat as U3O8 [$/kg U]	18.46	18.46	18.46			
specific conversion cost U3O8 to UF6 [$/kg U]	4.25	4.25	4.25			
price of Unat as UF6 [$/kg U]	22.71	22.71	22.71			22.71
exchange rate [EUR/$]	1.08	1.08	1.08			
Urenco/Eurodif enrichment plant						
theoretical tails disposal cost (DE) [$ million]	176.55	99.49	77.06	176.55	353.10	
theoretical tails disposal cost (UR) [$ million]	45.56	25.68	19.89	45.56	91.13	
theoretical tails disposal cost (US) [$ million]	30.75	17.33	13.42	30.75	61.49	
Tails upgrading Step 1						
specific transport cost [$/kg UF6]	1.50	1.50	1.50			
transport cost [$ million]	17.96	11.20	7.07	18.27	36.22	
specific separation work cost [$/SWU]	20.00	20.00	20.00			84.00
separation work cost [$ million]	15.76	13.49	24.20	37.69	53.45	43.25
separation work cost per kg Uneq produced [$/kg U]	14.39	12.22				
separation work cost per t UF6 feed [$/t UF6]	1522.08	2312.79	5355.10			
price paid for re-enrichment [$ million]	15.76	13.49	24.20			
market value of the product as UF6 [$ million]	24.86	25.08	69.08	94.16	119.02	69.08
theoretical tails disposal cost (UR) [$ million]	38.44	18.49	19.04	37.53	75.97	
theoretical tails disposal cost (US) [$ million]	25.94	12.47	12.85	25.32	51.26	
profit UE1NO = prod. val. ./. transp. ./. sep. [$ million]	-8.85	0.39	37.82	38.21	29.35	
profit UE1DE = UE1NO + avoid.disp. (DE) [$ million]	167.70	99.88	114.88	214.76	382.45	
profit UE1UR = UE1NO +avoid.disp. (UR) [$ million]	36.71	26.07	57.70	83.77	120.48	
profit UE1US = UE1NO + avoid.disp. (US) [$ million]	21.89	17.72	51.24	68.95	90.84	
profit R1UR = re-e.pr. ./. sep. ./. disp.(UR) [$ million]	-38.44	-18.49	-19.04	-37.53	-75.97	
profit R1US = re-e.pr. ./. sep. ./. disp.(US) [$ million]	-25.94	-12.47	-12.85	-25.32	-51.26	
Tails upgrading Step 2						
specific separation work cost [$/SWU]	20.00	20.00	20.00			84.00
separation work cost [$ million]	67.35	30.24	31.15	61.40	128.74	75.81
separation work cost per kg Uenr produced [$/kg U]	128.76	135.53	135.53	135.53	131.90	
separation work cost per t UF6 feed [$/t UF6]	7711.60	7200.72	7200.72	7200.72	7459.22	
market value of the product Uenr as UF6 [$ million]	75.39	32.16	33.13	65.29	140.68	140.68
tails disposal cost (UR) [$ million]	35.03	17.03	17.55	34.58	69.62	
tails disposal cost (US) [$ million]	23.64	11.49	11.84	23.33	46.97	
profit R2NO = R1 + prod. val. + avoid.disp. ./. separ. [$ million]	8.04	1.92	1.98	3.90	11.94	
profit R2UR = R2NO ./. disp. cost (UR) [$ million]	-26.99	-15.12	-15.57	-30.68	-57.68	
profit R2US = R2NO ./. disp. cost (US) [$ million]	-15.60	-9.58	-9.86	-19.44	-35.04	

ANNUAL COST BALANCE - OPT.B, Nov. 15, 2004	**Urenco**	**Ed. (neq)**	**Ed. (enr)**	**Ed. tot**	**Ure.+Ed.**	**Ref. Case**
General cost data						
price of Unat [$/lb U3O8]	20.25	20.25	20.25			
price of Unat as U3O8 [$/kg U]	52.65	52.65	52.65			
specific conversion cost U3O8 to UF6 [$/kg U]	10.00	10.00	10.00			
price of Unat as UF6 [$/kg U]	62.65	62.65	62.65			62.65
exchange rate [EUR/$]	0.77	0.77	0.77			
Urenco/Eurodif enrichment plant						
theoretical tails disposal cost (DE) [$ million]	247.63	139.54	108.09	247.63	495.26	
theoretical tails disposal cost (UR) [$ million]	63.91	36.01	27.90	63.91	127.82	
theoretical tails disposal cost (US) [$ million]	30.75	17.33	13.42	30.75	61.49	
Tails upgrading Step 1						
specific transport cost [$/kg UF6]	1.50	1.50	1.50			
transport cost [$ million]	17.96	11.20	7.07	18.27	36.22	
specific separation work cost [$/SWU]	20.00	20.00	20.00			110.00
separation work cost [$ million]	15.76	13.49	24.20	37.69	53.45	56.64
separation work cost per kg Uneq produced [$/kg U]	14.39	12.22				
separation work cost per t UF6 feed [$/t UF6]	1522.08	2312.79	5355.10			
price paid for re-enrichment [$ million]	15.76	13.49	24.20			
market value of the product as UF6 [$ million]	68.58	69.20	127.89	197.09	265.67	127.89
theoretical tails disposal cost (UR) [$ million]	53.92	25.93	26.71	52.64	106.55	
theoretical tails disposal cost (US) [$ million]	25.94	12.47	12.85	25.32	51.26	
profit UE1NO = prod. val. ./. transp. ./. sep. [$ million]	34.87	44.50	96.63	141.13	176.00	
profit UE1DE = UE1NO + avoid.disp. (DE) [$ million]	282.50	184.05	204.71	388.76	671.26	
profit UE1UR = UE1NO +avoid.disp. (UR) [$ million]	98.78	80.52	124.52	205.04	303.82	
profit UE1US = UE1NO + avoid.disp. (US) [$ million]	65.61	61.83	110.05	171.88	237.49	
profit R1UR = re-e.pr. ./. sep. ./. disp.(UR) [$ million]	-53.92	-25.93	-26.71	-52.64	-106.55	
profit R1US = re-e.pr. ./. sep. ./. disp.(US) [$ million]	-25.94	-12.47	-12.85	-25.32	-51.26	
Tails upgrading Step 2						
specific separation work cost [$/SWU]	20.00	20.00	20.00			110.00
separation work cost [$ million]	67.35	30.24	31.15	61.40	128.74	99.27
separation work cost per kg Uenr produced [$/kg U]	128.76	135.53	135.53	135.53	131.90	
separation work cost per t UF6 feed [$/t UF6]	7711.60	7200.72	7200.72	7200.72	7459.22	
market value of the product Uenr as UF6 [$ million]	149.11	63.61	65.52	129.14	278.24	278.24
tails disposal cost (UR) [$ million]	49.14	23.89	24.61	48.50	97.64	
tails disposal cost (US) [$ million]	23.64	11.49	11.84	23.33	46.97	
profit R2NO = R1 + prod. val. + avoid.disp. ./. separ. [$ million]	81.76	33.37	34.37	67.74	149.50	
profit R2UR = R2NO ./. disp. cost (UR) [$ million]	32.62	9.48	9.76	19.24	51.86	
profit R2US = R2NO ./. disp. cost (US) [$ million]	58.12	21.88	22.53	44.41	102.52	

Glossary

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

blendstock: uranium (*LEU, *Unat, or *DU) used for *downblending of *HEU

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 (< 0.711 weight-%)

DOE: U.S. Department of Energy

downblending: mixing of *HEU with *blendstock uranium, to obtain *LEU for nuclear fuel

DU: *depleted uranium

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

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

ESA: Euratom Supply Agency

feed: uranium introduced into the enrichment cascade as *UF_6

HEU: *highly enriched uranium

highly enriched uranium (HEU): uranium with an U-235 *assay of 20%, or higher (only used in nuclear weapons and in research reactors)

HLW: High-Level Radioactive Waste

IAEA: International Atomic Energy Agency

LEU: *Low Enriched Uranium

LLW: Low-Level Radioactive Waste

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.

Rosatom: Russian Federal Atomic Energy Agency (previously Minatom)

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: byproduct 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

Udep: *depleted uranium

Uenr: *enriched uranium

Unat: *natural uranium

Uneq: *„natural-equivalent" uranium

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

UO_2: **uranium dioxide** (chemical form used in fuel for *LWRs)
1 t UO_2 contains 0.8815 t U, while 1 t U is contained in 1.134 t UO_2

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

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BT-Drs. = Bundestags-Drucksache
NF = Nuclear Fuel

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