# C MODULES

## Uranium Enrichment

# Module C1

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## C1-MD. SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for 2017 Update:** FY 2017
- **Nature of this 2017 Module update from previous AFC-CBRs:** Escalation only with additional new text explaining current enrichment oversupply situation due to depressed nuclear fuel market. New (2017) analysis to support long term price projections is included in the text below.
- **Estimating Methodology for latest (2012 AFC-CBR) technical update from which this 2017 update was escalated:**
  - Extensive technical descriptions and market analyses were conducted for both the 2009 and 2012 AFC-CBRs. Escalation here is based on applying a 1.14 factor to the 2009 unit SWU cost ranges.

## C1-RH. REVISION HISTORY

- **Version of AFC-CBR in which Module first appeared**: 2004 as Module C. In 2005 AFC-CBR Module C was separated into Modules C1 and C2_to differentiate between true "process enrichment" and secondary enrichment achieved by blend-down of HEU to LEU. No true blending costs were available for Module C2, hence, no Unit Cost tables were produced.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** 2009 & 2012
- New technical/cost data which has recently become available and will benefit next revision:
  - **The enrichment market in 2017 is severely depressed primarily due to many reactors in Japan still being reviewed for restart post-Fukushima, but also due to lower projections for new nuclear and the premature closing of some US NPPs.**
  - **A market analysis in 2016 served as a "spot check" on the situation in the market for uranium enrichment. A summary of that spot check is included in Section C1-6.2.**

## C1-1. BASIC INFORMATION

Module C1 discusses the step in the nuclear fuel cycle where the $UF_6$ solid in cylinders from the conversion plant is processed to enrich the percentage of U-235 from 0.711% to the 3–5% typical of the enrichment used for light-water reactor (LWR) nuclear fuel fabrication. It involves receipt of $UF_6$ feed stock in 12.5-ton cylinders for evaporation, gas-phase enrichment operations, condensation of enriched $UF_6$ solid and depleted UF6 solid, and shipment of 2.3-ton enriched product cylinders to fuel fabricators. In this module, "SWU" is taken as shorthand for kg-SWU, the formal units for enrichment separative work, assuming that heavy metal mass flows will be gauged in kg.

The degree of enrichment is driven by the specific reactor requirements (pressurized or boiling water reactors) to meet desired burnup as well as other factors such as the possible presence of mixed oxide fuel or reprocessed uranium fuel assemblies in the same core . The product from the enrichment plant is called low-enriched uranium (LEU) if the enrichment is less than or equal to 20% U-235. At present, licensing constraints restrict the enrichment of LEU for civilian reactors to 5%. The product is highly enriched uranium (HEU) if the enrichment is greater than 20%. HEU was produced in support of nuclear weapons and marine propulsion programs and is currently used in some research reactors. During the enrichment process, the U-235 in the $UF_6$ is enriched from its natural state of 0.711% to the desired end state (3–5%). The by-product of the enrichment process is a large quantity of depleted uranium whose U-235 content is less than 0.711%. This material is known as the enrichment "tails" and typically has an assay in the range of 0.25 to 0.35% U-235. Such material is stable for several years and is currently stored as UF6 at the enrichment sites for future use (because it does have a significant fissile material loading) or conversion to more chemically stable oxide for long term storage and disposal (Module K1).

The basic enrichment market deals with supply of LEU. LEU can be supplied to the fuel manufacturer as a product of an enrichment process or by virtue of "down-blending" HEU with natural uranium or LEU. The overall demand can be satisfied by either or both of these methods. See Module C2 for details of HEU supply from military stockpile reductions.

The U.S. annual demand for LEU as of 2012 was approximately 21,500 tU. Worldwide, the demand for LEU is approximately 66,700 tU per year. The capacity of enrichment plants is measured in terms of "separative work units" (SWU or kg SWU). A SWU represents a quantity of separative work performed to enrich a given amount of uranium by a certain amount. It is a function of the amount of uranium processed, the degree to which it is enriched, as well as the level of depletion of the remaining tails. It is proportional to the amount of work required to move the gaseous uranium through the separation cascade. As an example, 3.8 SWUs are required to produce 1 kg of uranium enriched to 3% U-235 if the plant is operated to a tails assay of 0.25% or 5.0 SWUs are required if the plant is operated to a tails assay of 0.15%. With the lower tails assay, more SWUs are required; however, only 5.1 kg of natural uranium feedstock are required versus 6.0 kg for the higher assay. Therefore, SWU demand is established by the utilities looking at all aspects of the fuel cycle to determine how to best meet the reactor burn requirements. About 100–120 thousand SWUs are required to enrich the annual fuel loading for a typical 1,000 MWe light-water reactor.

The current worldwide enrichment requirements are about 39,000 million SWUs of which the U.S. demand is approximately 11,800 million SWUs. Although there are 21 enrichment facilities in operation, the world supply is dominated by four companies:

1. Eurodif (France)
2. Minatom (Russia)
3. URENCO (Germany, Netherlands, United Kingdom)
4. United States Enrichment Corporation (USEC) in the U.S.

The current world enrichment nameplate capacity is about 49.25 million SWUs. Thus an overcapacity exists. The current U.S. capacity of 11.3 million SWUs exists in one facility at Paducah, Kentucky. A second unit located in Portsmouth, Ohio, with an additional capacity of 7.4 million SWUs was placed in cold standby in March 2001.

The cost of enrichment represents ~30–40% of the overall cost of bundled LEUOX fuel manufacture. Enrichment services are highly competitive due to overcapacity and availability of LEU from blend-down of HEU (see Module C2). Enrichment cost is typically reported in U.S.$/SWU and includes related transportation costs to the fuel fabrication plant.

# C1-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

Globally, uranium is enriched on a commercial scale by one of two methods: gaseous diffusion and gas centrifugation. All operating uranium enrichment plants use $UF_6$ as feed (historically, uranium tetrachloride was used in some electromagnetic separation processes). The processes depend on the physical properties of the molecules, specifically the 1% difference in mass, to separate the isotopes of U-235 and U-238. The use of $UF_6$ is preferred because fluorine has only one stable isotope, and thus, the difference in processing is entirely due to the properties of the uranium isotopes. There are other methods such as laser isotopic enrichment and aerodynamic enrichment using separation nozzles and/or vortex tubes, but these are not commercially viable at this time. Worldwide gaseous diffusion (mainly in the U.S. and France) currently represents about 40% of capacity, with more recent facilities using the more cost-effective and energy-efficient gas centrifuge process. The gaseous diffusion plants have been durable and reliable, but are nearing the end of their design life with the focus on advanced centrifuge technology to replace this aging capacity. Table C1–1 shows that, with the retirement of diffusion-based facilities in France and the United States over the next decade, gas centrifuge plants will dominate the next generation of enrichment capacity.

Table C1–1 SWU or SWU equivalent market share by supply source (WNA 2009).

| Supply Source | 2007 | 2017 |
|---|---|---|
| Diffusion | 25% | 0 |
| Centrifuge | 65% | 93% |
| Laser | 0% | 3% |
| HEU Downblend[a] | 10% | 4% |
| a. SWU equivalent: derived from amount and enrichment of LEU produced via HEU downblending. | | |

Both gaseous diffusion and gas centrifugation begin with receipt of 12.5-t cylinders of solid $UF_6$ under a slight vacuum. The $UF_6$, when heated above 135°F in special autoclaves, becomes a gas and is the ideal feed for the two main commercial scale processes, which are described below.

**Gaseous Diffusion.** The gaseous diffusion process has been highly developed and used to produce both HEU and commercial reactor-grade LEU. The U.S. first employed gaseous diffusion during World War II and expanded its capacity after the war to produce HEU. Since the late 1960s, the U.S. facilities have been used primarily to produce commercial LEU, with the last remaining HEU capacity being shut down in 1992. China and France currently have operating diffusion plants. Russia's enrichment facilities have been converted from diffusion to centrifuge technology. Britain's diffusion facility was shut down and dismantled (Federation of American Scientists 2000).

The gaseous-diffusion process depends on the separation effect arising from the difference in rate of molecular effusion of the UF6 isotopes through a thin and porous barrier (i.e., the flow of gas through small holes). The frequency at which the different species pass through the tiny hole in the barrier is proportional to the speed of the molecule and inversely proportional to the square root of the molecular weight. On the average, lighter gas molecules travel faster than heavier gas molecules and, consequently, tend to collide more often with the porous barrier material. Therefore, lighter molecules are more likely to enter the barrier pores than are heavier molecules. For UF6, the difference in velocities between molecules containing U-235 and U-238 is small (0.4%). Consequently, the amount of separation achieved by a single stage of gaseous diffusion is small. Therefore, this process must be repeated in approximately 1,400 stages in a single cascade to achieve even LEU assays of 2.5 to 5%. The higher the desired enrichment, the more stages and recycle are required to get the desired product.

$UF_6$ is a solid at room temperature but becomes a gas when heated above 135°F. The solid $UF_6$ is heated to form a gas, and the gaseous diffusion enrichment process begins. The process separates the lighter U-235 isotopes from the heavier U-238. The gas is forced by a compressor through a diffusion cell consisting of a porous membrane (called “barrier”) with microscopic openings. Because the U-235 atoms are lighter, they have a slightly higher probability of reaching and passing through the membrane. As the gas moves, the two isotopes are separated, increasing the U-235 concentration and decreasing the concentration of U-238. Approximately 50% of the feed material passes through the membrane and is pumped off as lightly enriched product. The remaining material flows past the membrane, containing less U-235 and thus is slightly depleted. Passing through the membrane causes a pressure drop. After each stage, the gas must be depressurized, and the heat of compression must be removed (see Figure C1–1 and Figure C1–2).

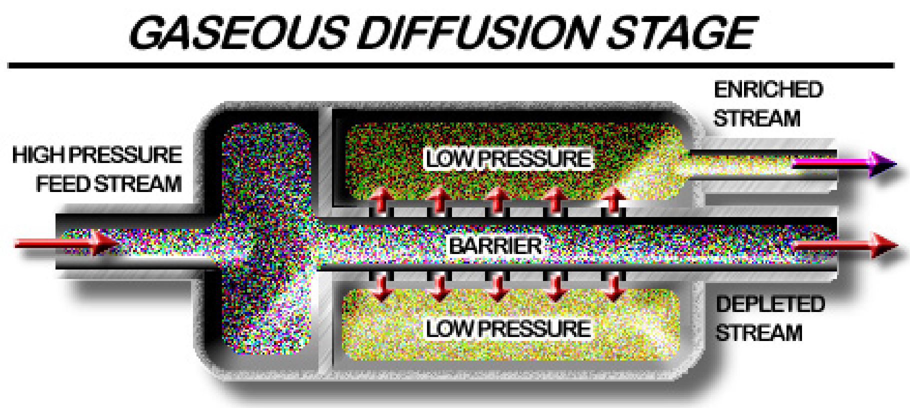


Figure C1–1 Gaseous diffusion stage (Federation of American Scientists 2009).

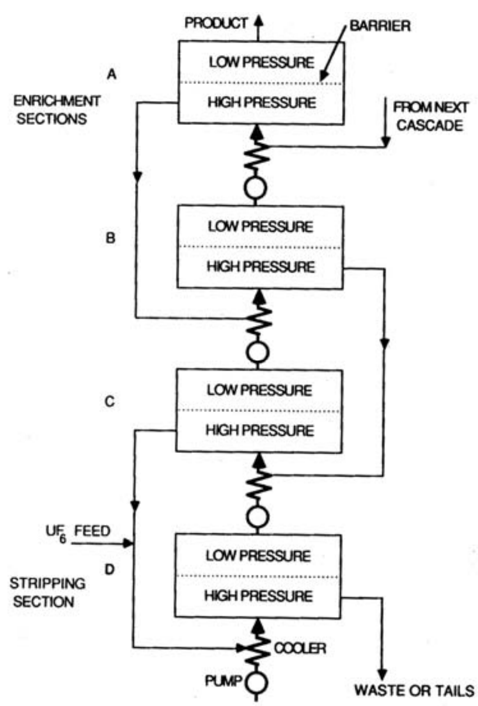


Figure C1–2 Gas must be depressurized, and the heat of compression must be removed.

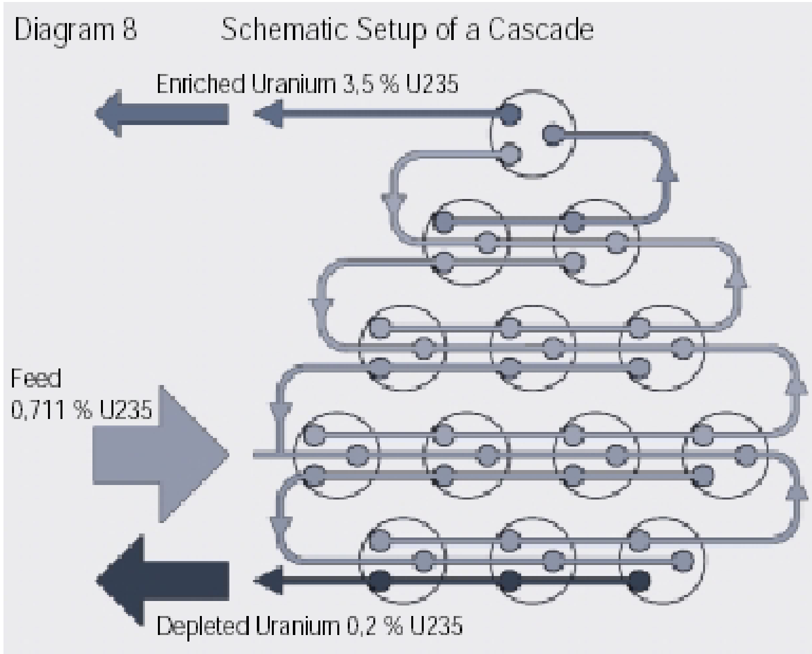


Figure C1–3 Gaseous diffusion cascade for enriching and stripping.

Figure C1–3 shows a typical gaseous diffusion cascade for enriching and stripping.

Diffusion equipment tends to be large and consumes significant amounts of energy (thousands of kwh per kg-SWU). The main components of a single gaseous-diffusion stage are (1) a large cylindrical vessel, called a diffuser or converter, that contains the barrier; (2) a compressor used to compress the gas to the pressures needed for flow through the barrier; (3) an electric motor to drive the compressor; (4) a heat exchanger to remove the heat of compression; and (5) piping and valves for stage and interstage connections and process control. The entire system must be essentially leak free, and the compressors require special seals to prevent both out-leakage of $UF_6$ and in-leakage of air. In addition to the stage equipment, auxiliary facilities for a gaseous-diffusion plant include a large electrical power distribution system, cooling towers to dissipate the waste process heat, a fluorination facility, a steam plant, a barrier production plant, and a plant to produce dry air and nitrogen. The process is energy intensive requiring over 2,500 kWh/SWU. A gas diffusion plant uses approximately 4% of the energy that can be generated with its enriched uranium.

At the end of the process, the enriched $UF_6$ gas is withdrawn from the pipelines and condensed back into a liquid that is poured into containers. The $UF_6$ is then allowed to cool and solidify in 2.3-t cylinders before it is transported to fuel fabrication facilities where it is turned into fuel assemblies for nuclear power reactors. The depleted “tails” UF6 is also cooled and stored in larger cylinders, generally on site. Concerns about long-range chemical reactivity of DUF6 in corrodible steel cylinders has caused most countries to consider “de-converting” the DUF6 to more stable solid oxide forms such as U3O8. (Module K considers this fuel cycle step in details. In terms of total mass, DUF6 is the largest radioactive waste material in the entire once-through nuclear fuel cycle.

**Gas Centrifuge.** The gas centrifuge uranium enrichment process uses a large number of rotating cylinders in a sequence. These sequences of centrifuge machines, called trains, are interconnected to form cascades. Gaseous $UF_6$ is fed into a cylindrical rotor that spins at high speed inside an evacuated casing. Because the rotor spins very rapidly, centrifugal force results in the gas occupying only a thin layer next to the rotor wall, with the gas moving at approximately the speed of the wall. The centripetal forces induced by the circular motion of the gases (about a million times the gravitational force on the gas) also causes the heavier $^{238}UF_6$ molecules to tend to move closer to the outer wall than the lighter $^{235}UF_6$ molecules, thus partially separating the uranium isotopes. This separation is increased considerably by a relatively slow axial countercurrent flow of gas within the centrifuge that concentrates enriched gas at one end and depleted gas at the other. $UF_6$ depleted of U-235 flows upward adjacent to the rotor wall, while the $UF_6$ enriched in U-235 flows downward closer to the axis. The two gas streams are continuously removed through small pipes. The separative capacity of a single centrifuge increases with the length and radius of the rotor and the rotor wall speed. Consequently, centrifuges containing long, high-speed rotors are the goal of centrifuge development programs.

The primary constraint upon further enhancement of the separation factor achievable in a single centrifuge unit is imposed by the rotor material. Specifically, the maximum tangential velocity of the rotor is limited by the square root of its yield strength to density ratio. Therefore, strong lightweight materials such as aluminum and titanium are favored. The length of a centrifuge unit is often constrained by the need to avoid exciting a destructive resonant oscillation.

Although the capacity of a single centrifuge is much smaller than that of a single diffusion stage, its capability to separate isotopes is much greater. Centrifuge stages normally consist of a large number of centrifuges in parallel. Such stages are then arranged in cascade similarly to those for diffusion. Although the separation factors obtainable from a centrifuge are large compared to gaseous diffusion, several cascade stages are still required to produce even LEU material. In the centrifuge process, however, the number of stages in a series may only be 10 to 20, instead of a thousand or more for diffusion. As was the case for the diffusion cascade, the stream that is slightly enriched in U-235 is withdrawn and fed into the next higher stage, while the slightly depleted stream is recycled back into the next lower stage. Eventually, enriched and depleted uranium are drawn from the cascade at the desired assay. Significantly more U-235 enrichment can be obtained from a single unit gas centrifuge than from a single unit gaseous diffusion barrier. Each cascade is capable of producing the desired separation. Many cascades must be run in parallel to gain the desired total plant throughput. However, this lends flexibility to the operation and supports ease of modular growth. This is in stark contrast to a diffusion plant where the many stages must run in one cascade to obtain the final product (WNA 2009).

The end of the process is basically the same as the gaseous diffusion process; the enriched $UF_6$ gas condensed into a liquid that is poured into containers before being further cooled and transported in a solid form to fuel fabrication facilities. Figure C1–4 and Figure C1–5 show schematics of typical gas centrifuges used for U-235 enrichment.

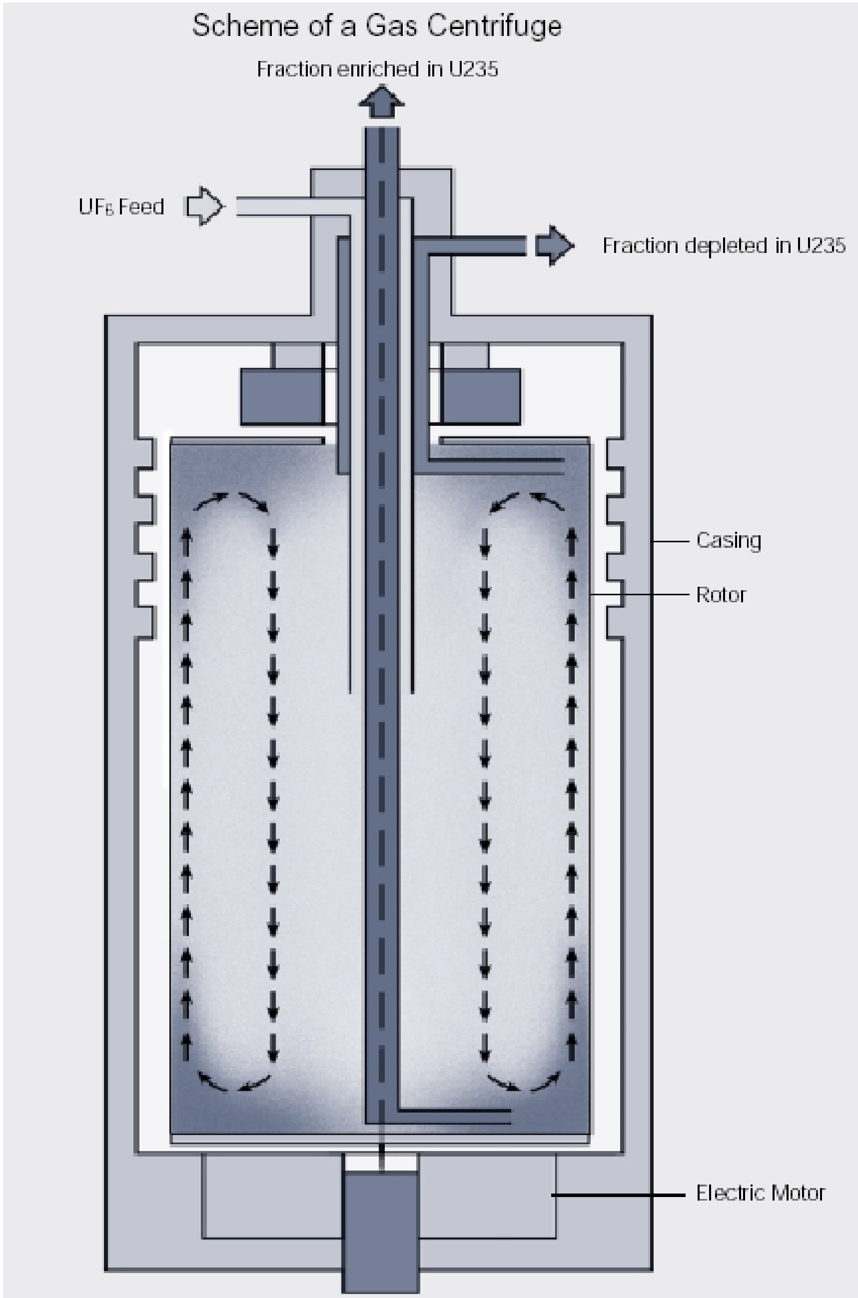

Figure C1–4 Gas centrifuge.

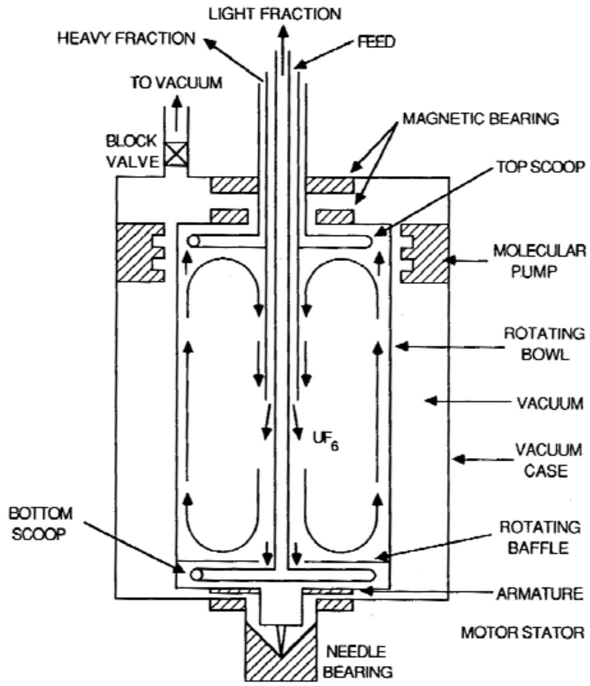


Figure C1–5 A schematic showing the Zippe centrifuge.

One of the key components of a gas centrifuge enrichment plant is the power supply (frequency converter) for the gas centrifuge machines. The power supply must accept alternating current (ac) input at the 50 or 60-Hz line frequency available from the electric power grid and provide an ac output at a much higher frequency (typically 600 Hz or more). The high-frequency output is fed to the high-speed gas centrifuge drive motors (the speed of an ac motor is proportional to the frequency of the supplied current). The centrifuge power supplies must operate at high efficiency, provide low harmonic distortion, and provide precise control of the output frequency.

The casing not only maintains a vacuum, but must also contain the rapidly spinning components in the event of a failure. If the shrapnel from a single centrifuge failure is not contained, a “domino effect” may result and destroy adjacent centrifuges. A single casing may enclose one or several rotors.

A notable feature of the gas centrifuge process is that the plant capacity can be expanded on a modular basis. Capacity can be increased according to market demand. This leads to substantial economic advantages and allows advanced technology to be installed in each increment of capacity. Because of the development of almost friction-free bearings, the electrical consumption of a modern gas centrifuge facility is much less than that of a gaseous diffusion plant requiring as little as 50 kWh/kg SWU (roughly 2% of the gaseous diffusion requirement).

**Laser Isotopic Separation.** The Atomic Vapor Laser Isotopic Separation process (AVLIS) and the similar French process SILVA were extensively studied in the 1990s by the U.S., France, and Japan. These processes have not proven to be commercially viable in the short term, and the U.S. and France have stopped development efforts.

**SILEX Process.** USEC secured exclusive worldwide rights to the commercial use of the SILEX laser-based technology for enriching uranium in 1997, working in partnership with SILEX Systems LTD., in Australia. After funding it for 6 years, USEC announced its withdrawal from the SILEX project in 2003, despite continuing positive results. SILEX and General Electric Company (GE) signed an exclusive Commercialization and License Agreement for the SILEX Uranium Enrichment Technology in 2006

(SILEX Systems, LTD 2006). If successfully deployed, SILEX, a molecular laser separation process using $UF_6$, would selectively separate U-235 in a manner that requires lower power consumption, lower capital cost, and lower tails assay. Similar to gas centrifuges, SILEX could be implemented in a modular manner. GE-Hitachi is currently evaluating the SILEX process in a significant scale engineering prototype facility.

The SILEX process is illustrated schematically in Figure C1–6. The physical principle on which the process is based is the isotopic shift between $^{235}UF_6$ and $^{238}UF_6$ for certain vibrational infrared light absorption bands. The product stream, enriched in the excited $^{235}UF_6$, is collected and may be subjected to additional enrichment stages if necessary.

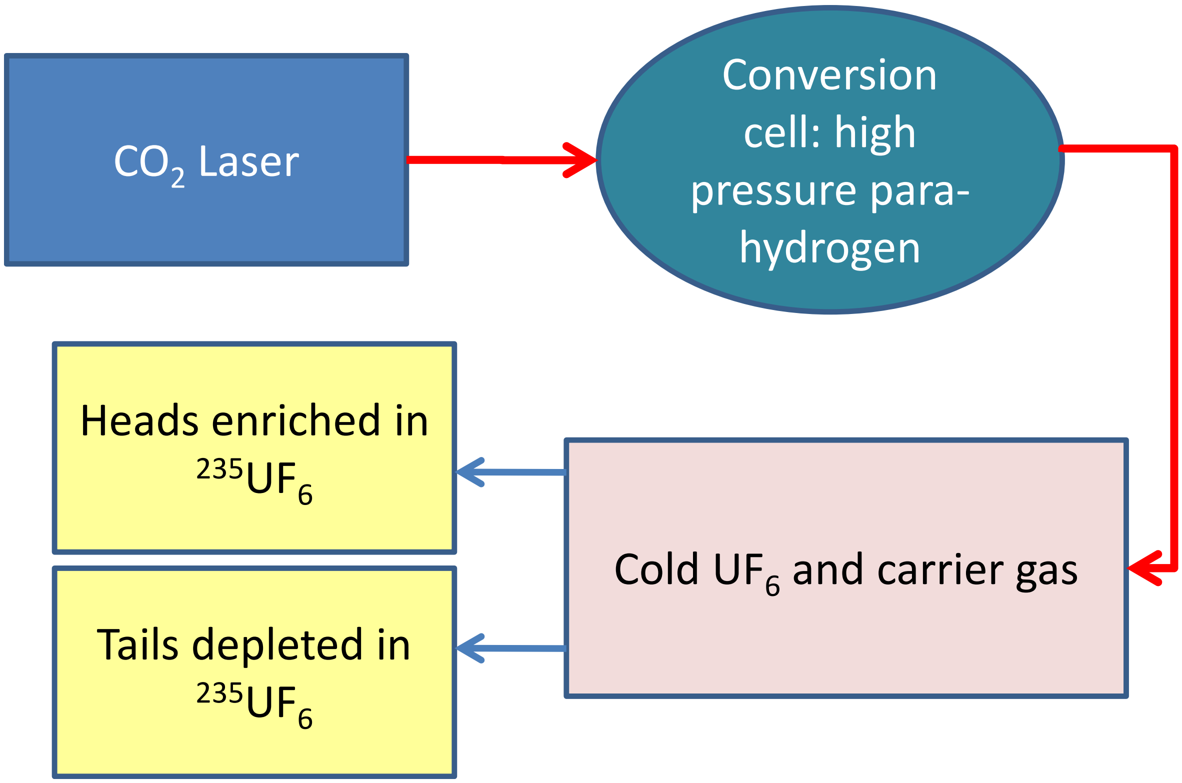

Figure C1–6 Schematic of SILEX process.

Although SILEX engineering and performance details are proprietary, the technical considerations that have hampered laser-driven enrichment in the past are known. These include the repetition rate of the $CO_2$ laser, which must reach several hundred cycles per second for the process to be commercially viable. Low repetition rates harm throughput and separation efficiency because only a small fraction of the material in the target tank is exposed to the light during a given time interval. Second, the $UF_6$ must be maintained at low temperature to limit molecular kinetic energy so that the absorption lines are resolved. But $UF_6$ is solid at low temperatures and atmospheric pressure, so its molecular density must be quite low to preclude condensation. (Lyman 2005) estimates that densities higher than $10^{15}$ molecules/cc may be difficult to achieve, with consequent implications for throughput.

If these obstacles are overcome, the technology could offer exceptionally high stage separation factors (Table C1–2). This could in turn render further enrichment of existing enrichment tails much more attractive than is presently the case. The technology may also be especially useful if applied to reprocessed uranium, as $^{236}U$ need not be concentrated along with $^{235}U$ in the product stream as is the case for existing technologies that rely upon mass differences. On May 22, 2006 GE and SILEX Systems announced plans to move forward on a test loop at the GE Global Nuclear Fuel—Americas site in Wilmington, North Carolina. This test loop is now operational; subsequent developments are described in Section C1-4.1.1, Supply. Table C1–2 summarizes key performance metrics of the three most prominent enrichment technologies.

Table C1–2 Performance metrics of enrichment technologies.

| Technology | Energy Consumption (kWh/SWU) | Stage Separation Factor[b] |
|---|---|---|
| Diffusion | 2000–2500 | 1.004 |
| Centrifuge | 50–100 | 1.2–1.6 |
| Laser (SILEX)[a] | 15–150 | 2–20 |

SILEX values are estimates; exact figures are considered trade secrets. The quoted range for the stage separation factor was taken from (SILEX 2008). The upper bound for energy consumption was taken from (Whittaker 2005).

The stage separation factor is defined as the U-235:U-238 ratio in the heads (i.e., the product stream_ of a single stage) divided by the U-235:U-238 ratio in the tails. For example, consider a single machine whose feed is natural uranium at 0.72% U-235. If it is operated in a manner typical of commercial enrichment cascades, the U-235:U-238 ratio in the heads divided by the U-235:U-238 ratio in the feed will be the square root of the stage separation factor. Thus for diffusion, the product from that single machine would have a U-235 enrichment of 0.7214%. Taking a stage separation factor of 1.4, the midpoint of the range given in Table C1-2, the product from a single centrifuge would be enriched to 0.851%. For SILEX with a stage separation factor of 10, the product enrichment would be 2.24%.

**Other Separation Technologies.** Numerous chemical, ion exchange, electromagnetic, aerodynamic and plasma separations processes have been investigated, but none are being seriously considered at this time for large-scale commercial uranium enrichment applications.

## C1-3. PICTURES AND DIAGRAMS

Large commercial enrichment plants are in operation in France, Germany, Netherlands, United Kingdom, U.S., and Russia with smaller plants elsewhere. The following picture shown in Figure C1–7 is the European Gaseous Diffusion Uranium Enrichment Consortium's (EURODIF's) Tricastin gaseous diffusion enrichment plant in France. Note the four reactors in the foreground that supply 3000 MWe of power to the enrichment facility and the large production facilities beyond the cooling towers.

Figure C1–8 shows the USEC Gaseous Diffusion Building in Paducah, Kentucky. Figure C1–9, Figure C1–10, and Figure C1–12 show the URENCO gas centrifuge enrichment plant at Gronau, Germany.

Figure C1–7 EURODIF's George Besse Gaseous Diffusion Enrichment Plant.

Figure C1–8 United States Enrichment Corporation Gaseous Diffusion Production Building.

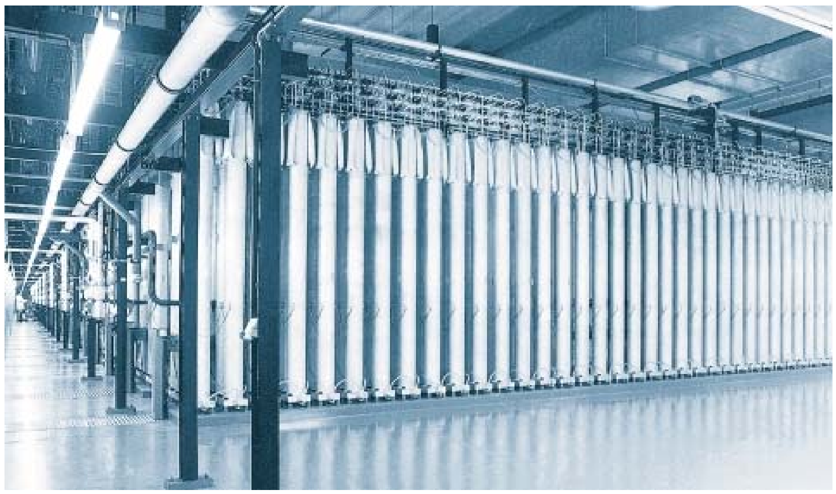

Figure C1–9 Separation Hall with centrifuges at the Gronau Enrichment Plant, Germany.

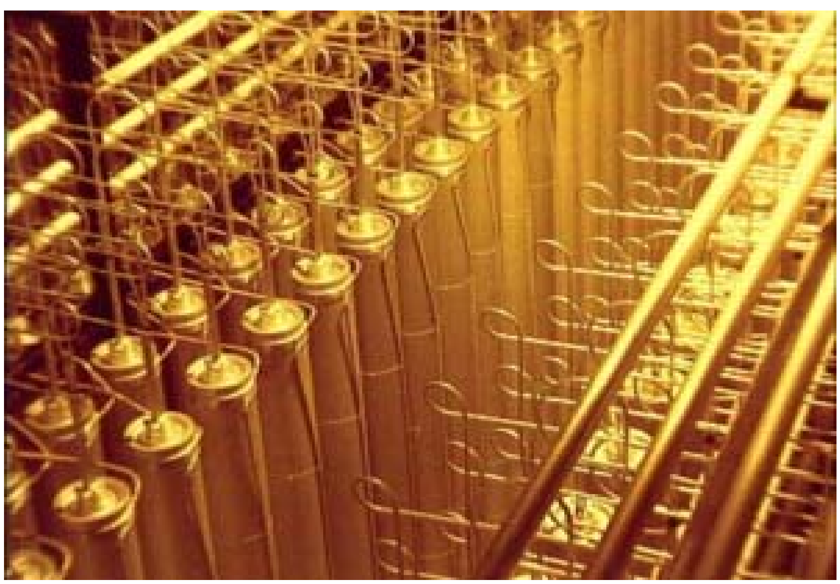

Figure C1–10 Top view of a bank of centrifuges at a URENCO gas centrifuge plant.

Figure C1–11 Enriched UF6 product container being loaded into an overpack for shipment.

## C1-4. MODULE INTERFACE DEFINITION

The need for enrichment services is highly dependent on Modules A, C2, D1, D2, and K. Raw uranium pricing impacts the source uranium cost of conversion. The availability of mixed oxide, reprocessed uranium, and/or blend down of highly enriched uranium impacts the demand for enrichment services from $UF_6$. Timing of fuel fabrication also impacts the need for conversion services. In addition to real-time feed and product needs, decisions relative to inventory levels along the front-end of the fuel cycle will have impact on this enrichment module. The possible requirement that enrichment plant “tails” be stored in a less chemically active form than UF6 may impact the operations and economics of uranium enrichment plants. The enrichment price in some cases might include the DUF6 deconversion and subsequent deconverted product disposal costs, since the tails may be viewed as a waste liability. Deconversion and disposal are discussed in Module K1.

The key cost dependencies on supply and demand are discussed in the following section.

### C1-4.1 Supply

The shift in the supply profile away from the elderly, energy-intensive diffusion process and toward centrifuge technology that began in the 1970s is nearing completion. As of 2009, two large diffusion plants remained in operation, Areva/EURODIF’s Georges Besse facility at Tricastin, France and the USEC Paducah Gaseous Diffusion Plant. Areva formally retired Besse from service on June 7, 2012 (AREVA 2012a). The Paducah facility was on the point of shutting its doors in 2012 as well, but in May 2012 an agreement was concluded to re-enrich 9,000 tonnes of DOE-supplied depleted uranium hexafluoride into 480 tonnes of LEU reactor fuel for the Columbia Nuclear Generating Station and TVA-operated reactors (NSNT 2012a). This agreement will allow Paducah to remain in operation into 2013. Its future beyond that date is uncertain, as its current operating license expires on December 31, 2013.

Together these diffusion plants accounted for a name plate annual capacity of over 22,000,000 SWU. Table C1–3 shows that several new centrifuge and laser-based enrichment plants are coming online or planned, and the capacity of a number of existing facilities is being expanded. Together these additions, if completed, will surpass the capacity of the retiring gaseous diffusion plants by more than 20,000,000 SWU.

In the United States, the Urenco / Louisiana Energy Services Urenco USA facility entered production in June 2010. Production at this facility is slated to increase to its design level of 5,700,000 SWU/yr by 2015. Three other facilities are under construction or planned in the US. Areva’s schedule for the 3,300 SWU Eagle Rock plant in Idaho Falls, ID has been delayed, but the company has announced plans to begin construction in 2014, or 2013 if suitable financing can be obtained (AREVA 2012b). As of July 2017 these plans are on hold because of market conditions.

GE-Hitachi will construct the first commercial laser-based enrichment plant in Wilmington, NC. The US NRC has issued an environmental impact statement (EIS) for this facility (NRC 2012) and a combined construction and operating license may be granted as early as the second half of 2012 (World Nuclear News 2012). If that schedule is kept, GE-Hitachi anticipates production to commence in 2014 with full capacity, 3,500,000 SWU/yr, achieved by 2020. As of July 2017 GE-Hitachi has put its plans on hold, most likely due to market conditions.

The fate of the proposed 3,800,000 SWU/yr USEC American Centrifuge Project (ACP) remains uncertain. In early 2012 USEC announced that it would exhaust available funding by May 31 and lobbied DOE to present its case for additional funding to Congress (USEC 2012). Subsequently, the US House and Senate inserted $150M in funding into bills moving through Congress (NSNT 2012b). USEC has argued that maintenance of American-owned and operated enrichment capacity is an issue of national security as well as domestic energy security. But as of mid-2012 USEC has been unsuccessful in its efforts to secure a $2B loan guarantee from the US government. As of July 2017 market conditions are also negatively impacting ACP prospects.

Production began in 2011 at the AREVA Georges Besse II Plant. By 2016, this plant is slated to reach a capacity of 7,500,000 SWU/yr, meeting the French SWU requirement that had been served by the retired Besse gaseous diffusion plant. Besse II will not provide France with substantial capacity for export, although Korean, Japanese and other French corporate partners each own small stakes in Besse's operating company.

Table C1–3 Uranium enrichment capacities.[1]

| Operator / Plant(s) | June 2012 Capacity (SWU/year)[1] | Planned 2020 Capacity (SWU/year)[2] | Technology, Notes |
|---|---|---|---|
| CNNC/Lanzhou, Hanzhong, China | 1,900,000 | 6,000,000-8,000,000 | Lanzhou: 500,000 SWU/yr centrifuge, 900,000 SWU/yr diffusion. Hanzhong: centrifuge |
| AREVA/Georges Besse II, France | 1,500,000 | 7,500,000 | Centrifuge: began production April 2011 |
| AREVA/Eagle Rock, USA | 0 | 3,300,000 | Centrifuge, construction may begin 2013-14 |
| USEC/Paducah GDP & American Centrifuge Project, USA | 11,300,000 | 3,800,000 | Paducah: diffusion, likely to be decommissioned between 2013 & 2016. ACP: centrifuge, prospects uncertain |
| Urenco/Gronau, Germany; Almelo, Netherlands; Capenhurst, UK | 14,250,000 | 12,300,000 | Centrifuge |
| Urenco/Urenco USA | 400,000 | 5,700,000 | Centrifuge, began production June 2010 |
| Tenex/Angarsk, Novouralsk, Zelenogorsk, Seversk, Russia | 16,600,000 | 30,000,000-35,000,000 | Centrifuge |
| JNFL/Rokkasho, Japan | 1,050,000 | 1,500,000 | Centrifuge |
| GE-Hitachi, Global Laser Enrichment, USA | 0 | 3,500,000 | SILEX, production may begin in 2014 |
| **TOTAL** | **47,000,000** | **73,600,000 – 80,600,000** | |

1. Only plants having greater than 250 tU/yr capacity reported. Data Source: (WISE 2009).
2. Only plants having greater than 250 tU/yr capacity reported. Data Source: (WNA 2012).

A planned expansion of Tenex facilities in Russia, on the other hand, may position Russia with more than 20,000,000 SWU/yr of capacity above domestic needs. The centerpiece of this expansion is the International Uranium Enrichment Center (IUEC) at Angarsk, a joint venture between Tenex and Kazatomprom. Founded in 2007, IUEC is intended to become a model supplier of assured fuel cycle services along the lines of nuclear fuel bank concepts extending back to the 1950s & 1960s era of Atoms for Peace (Loukianova 2008). To this end, the Russian government removed Angarsk from Russia's list of military-supporting facilities and placed it under IAEA safeguards. As discussed in Section C1-2, this expansion will grant Russia considerable leverage over the enrichment market.

The bilateral (U.S.-Russia) "Suspension Agreement" amendment was reached in February 2008. This amendment to a 1992 antidumping agreement will provide Russia limited access to the U.S. enrichment market. The import quotas shown in Table C1–4 have been established for 2011–2020. Note the jump from 2013–2014 that is intended to act as partial compensation for the termination of supplies from the HEU Agreement (Neely 2008). Since Russian SWU are comparatively cheap to produce (see Section C1-8) and Russian capacity is underutilized it is reasonable to expect these quotas to be fully met. Moreover, Russian SWU may play an even larger role after 2020 when the "Suspension Agreement" amendment stipulates the termination of limits on Russian SWU exports to the U.S. (Rothwell 2009). It is important to note that the amendment decreases the uncertainty surrounding SWU availability after 2013 and should exert a stabilizing influence on prices. See Module C2 for further discussion concerning supply from downblend of HEU.

Table C1–4 Importation quotas (millions of SWU) for Russian enrichment services under the Suspension Agreement amendment.

| Year | Import Limit | Year | Import Limit |
|---|---|---|---|
| 2011 | 0.10 | 2016 | 2.90 |
| 2012 | 0.15 | 2017 | 2.96 |
| 2013 | 0.25 | 2018 | 2.98 |
| 2014 | 2.93 | 2019 | 3.07 |
| 2015 | 2.75 | 2020 | 3.11 |

In a January 26, 2009 reversal of a circuit court ruling, the U.S. Supreme Court ruled in favor of USEC in an anti-dumping case it filed against Eurodif. Therefore, a 20% tariff on Eurodif SWU levied by the Commerce Department in 2000 was reinstated. This decision set an important precedent: the Supreme Court in effect ruled that SWU should be considered a "good" rather than a "service." Therefore, enrichment services may continue to be subject to tariffs under anti-dumping laws (NTI 2009).

## C1-4.2 Demand

Table C1–5 breaks down by country and region the forecasted near-term (2015) world SWU requirement of 55,000,000 SWU/yr. Given the total installed capacity in 2012, 47,000,000 SWU/yr, it can be seen that the tightness in the enrichment market may continue, with little or no capacity above requirements until the latter half of the 2010s when large projects in Russia, the USA and France come fully online.

Table C1–5 Forecasted SWU Requirements, 2015 (SWU/yr).[1]

| Country | SWU |
|---|---|
| Mexico | 148,000 |
| USA | 11,665,000 |
| Belgium | 800,000 |
| Czech Republic | 465,000 |
| Finland | 595,000 |
| France | 6,120,000 |
| Germany | 1,300,000 |
| Hungary | 245,000 |
| Netherlands | 55,000 |
| Slovak Republic | 362,000 |
| Spain | 1,000,000 |
| Sweden | 1,040,000 |
| Switzerland | 200,000 |
| United Kingdom | 810,000 |
| Japan | 7,210,000 |
| Korea | 4,200,000 |
| TOTAL, OECD | 36,215,000 |
| TOTAL, Others | ~19,000,000 |
| **World Total** | **55,215,000** |

1. OECD countries forecast from WNA 2012, (others from WNA 2011).

On the other hand, the contemporary shortfall in primary supplies of enrichment services, like that of primary supplies of uranium, is being made up by an important secondary source of supply. This is the down blending of HEU in the United States and Russia. HEU down blend displaces enrichment requirements since the HEU need only be mixed with natural (NU), slightly enriched (SEU: typ ~1% U-235) or depleted uranium (DU) to attain low enriched uranium (LEU) fuel with the proper enrichment for commercial reactors. Figure C1–12 shows that through 2013, when the down blending agreement between the US and Russia expires, approximately 20% of world SWU requirements are being met by this secondary source. The World Nuclear Association (WNA 2012) projects that even after the 2013 expiration of the agreement, HEU down blend will continue to meet ~4,000,000 SWU of requirements. See **Module C2: HEU Blend-Down** for further information.

Ref. C1-16 projects the three SWU demand scenarios shown in Figure C1–12. Although the reference and upper demand scenarios imply requirements exceeding supply after 2020, it is important to note that the supply depiction only includes existing, under construction and announced capacity additions (this is also the case for the data of Table C1–1). As of 2012, no announcements of capacity expansions after 2020 have been made. But if SWU demand followed a trajectory like the reference or upper demand scenarios in Figure C1–12, suppliers would doubtless act to build new capacity. Likewise, if demand does not accelerate, it is probable that some of the expansions and new projects indicated in Table C1–1 will be delayed or abandoned by their owners.

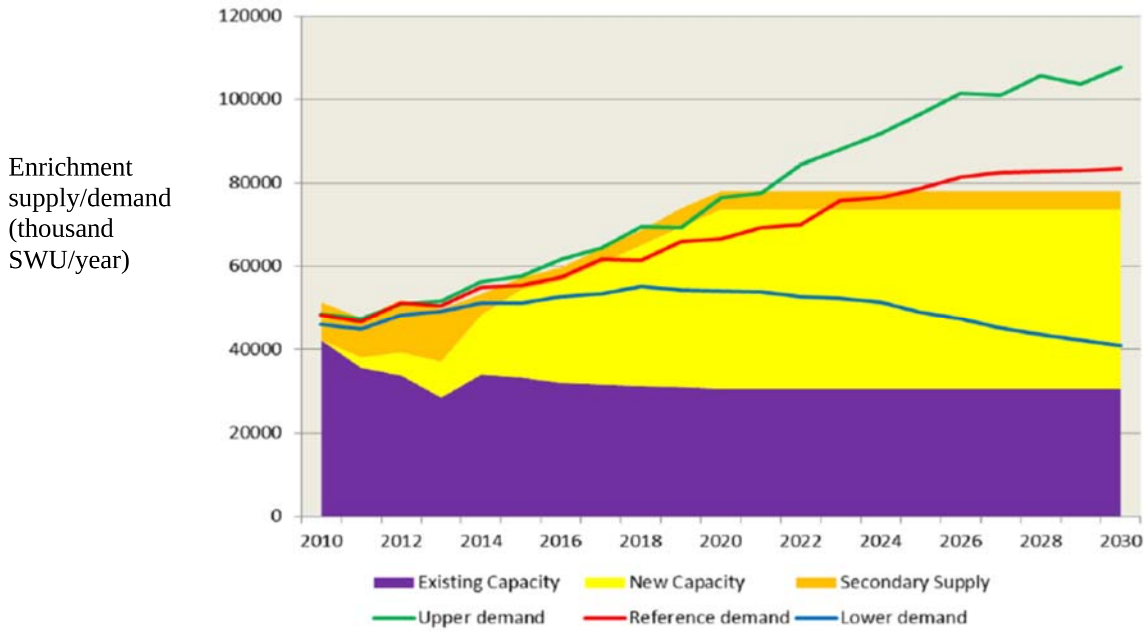


Figure C1–12 World Nuclear Association forecast of enrichment supply and demand (thousand SWU/yr) through 2030. Figure source: (WNA 2011).

## C1-4.3 Interaction with Uranium Prices

There is an important interaction between Cost Modules A and C1. Figure C1–13 depicts the relationship between raw uranium requirements and the enrichment tails assay. Simply stated, if more U-235 is separated (i.e., lower tails assay) per unit of feed, then less feed (i.e., natural uranium) is needed.

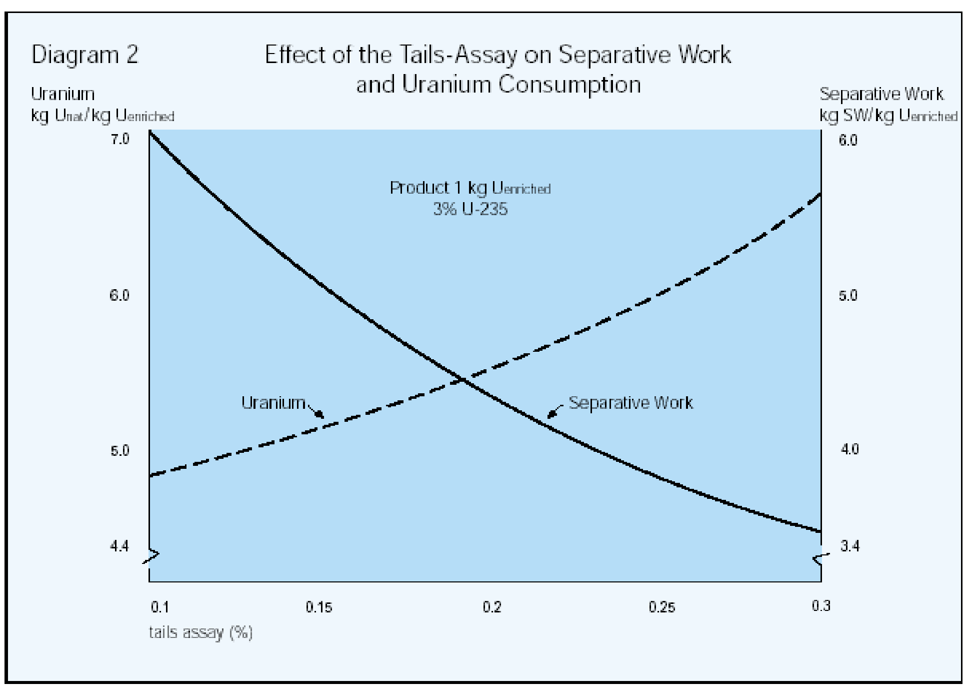


Figure C1–13 Relationship between raw uranium requirements and the enrichment tails assay.

As an example of this coupling, the optimal tails enrichment as a function of uranium-to-SWU price ratio ($/kgU as $UF_6$ per $/SWU) has been calculated by Thomas Neff of Massachusetts Institute of Technology (MIT) (Neff 2006). His results are shown in Figure C1–14. From 2002 through late 2006, as uranium prices increased at a greater rate than SWU prices, the optimal tails enrichment dropped from about 0.35% to 0.22%. Utilities' shift to lower tails fractions should, over time, serve to reduce primary uranium prices, with attendant upward pressure on SWU prices that would accompany higher demand. This effect is evidently too small to stem the rise in uranium prices. At the time Neff prepared his figure, the U in $UF_6$:SWU price ratio was about 1.0; as of May 2007 it reached 2.2 as the U in $UF_6$ price rose from $134 (August 2006) to $305 (May 18, 2007), while the SWU price rose only slightly, from $130/SWU to $138/SWU.

At a $UF_6$:SWU price ratio of 2.2, the optimal tails enrichment would be 0.15%. Information regarding recent enrichment contracts and volumes is difficult to obtain; however, inherent lead times ensure that tails enrichments are not yet this low. Nonetheless, over the medium term and subject to SWU supply constraints, this elasticity of demand ensures that:

1. Uranium and SWU prices will have a positive correlation
2. Upward (or downward) price pressure within one of these industries will be mitigated to an extent.

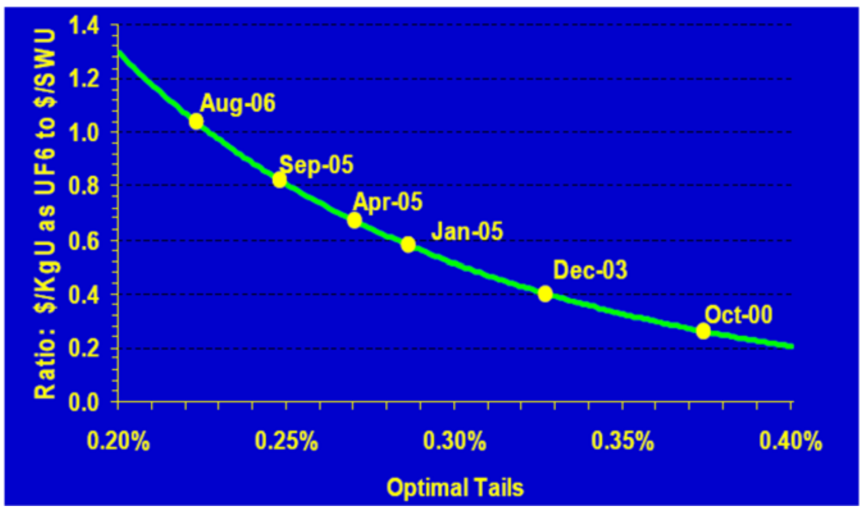


Figure C1–14 Optimal tails as a function of ratio of uranium to SWU price.

The reality of the supply-demand discussion is that is it a very dynamic and extremely competitive market. Key interactive factors include:

- Tails assay versus natural uranium price and supply.
- Commercialized HEU to LEU availability (both Russian and U.S.) and timing (blend-down can occur with natural uranium, LEU, enrichment tails, and/or reprocessed uranium) (see Module C2).
- Further reductions in nuclear stockpiles and government inventories of uranium in all forms (see Module C2).
- Openness of emerging enrichment suppliers especially from currently restricted markets. Because of past dumping practices, several countries and the Commonwealth of Independent States are not permitted to enter the competitive market or are currently heavily taxed to do so. Under the amendment to the Russia/U.S. "Suspension Agreement," this restriction on Russian SWU will be partially, and after 2020 perhaps fully, lifted. Protections extend beyond Russian SWU:
- Cost versus reliability and flexibility (reliability is critically important).

- Demand for higher enrichment because of deeper burn reactor operations or to support use of mixed oxide fuel (and to address the higher enrichment needs of very high temperature gas reactors).
- Continued integration of fuel cycle companies to integrate all aspects of the fuel cycle up through fuel fabrication.
- Enriched uranium product procurement versus utility procurement of natural uranium, conversion, and enrichment services (changes price structure due to avoidance of carrying costs from uranium purchase to fuel delivery).
- Much of the existing infrastructure is getting quite old. New facilities, while capital intensive, will be more cost effective, reliable, capable of modular expansion, and have more flexibility in products.

These factors should all work to keep the price of SWU fairly stable with moderate price increases to support new supply balanced by an overall production cost decrease as electricity-hungry diffusion plants are retired in favor of centrifuge facilities.

## C1-5. SCALING CONSIDERATIONS

New additions to supply are planned. In cases like the U.S. and France, the new facilities will permit the more costly gaseous diffusion plants to be replaced by the more efficient gas centrifuge plants. The gas centrifuge technology is relatively mature with ongoing work to improve efficiency even further. Costs are reasonably well understood and capacity can easily be added in a cost-effective modular basis. Therefore, scale-up is not a process or cost concern for this technology. A general cost per SWU can be expected to apply over the range anticipated for future growth.

## C1-6. COST BASES, ASSUMPTIONS AND DATA SOURCES

The historical spot market price of enrichment services is shown in Figure C1–15. Over 95% of enrichment service transactions between 2009 and 2011 were settled through long-term contracts (Schwartz et al 2012), and **the forecasts made here are intended to reflect contract prices**. But the **spot market price is nonetheless an important indicator of market effects as well as the direction in which future contract prices will move**.

Over the time period covered by Figure C1–14, the U-235 content of depleted uranium tails has varied considerably. Specified by the purchaser of enrichment services and attained by adjustment of the enrichment cascades, it governs the tradeoff between uranium and SWU consumption. A high U-235 content in tails increases NU requirements and decreases SWU requirements, per unit of LEU produced. Since the mid-2000s, elevated uranium prices (see Module A1) have led utilities to request lower tails U-235 content, reducing their NU requirements but increasing SWU consumption. Hence, the tails U-235 content prevailing across the industry has declined from 0.3-0.35% prior to 2003-4 to ca. 0.22% in 2012 (WNA 2011).

The impending (2013) end of the US-Russia HEU agreement, which will reduce a key secondary source of SWU (see Module C2), has exacerbated the upward pressure on prices. Also, as mentioned in Section C1-1.2, requirements and aggregate supply are presently closely matched, leading to a tight market. This situation is transient, arising from the closure of large gaseous diffusion plants in the US and France and gradual replacement of the retired capacity with new centrifuge and laser facilities. In the recent past, then, the spot price increase was likely further spurred by the sensitivity of the energy-intensive gaseous diffusion process to the escalating price of electricity (Schwartz et al 2012). On the other hand SWU spot prices have declined to $130/SWU following a 2009 peak of over $160/SWU and it will be argued that they will likely drop further. Note that the prices in Figure C1–15 are not adjusted for inflation: in real terms, the 2012 price ($130/SWU) is lower than the CPI-adjusted 1995 price ($90/SWU in 1995 dollars, $135/SWU in 2012 dollars).

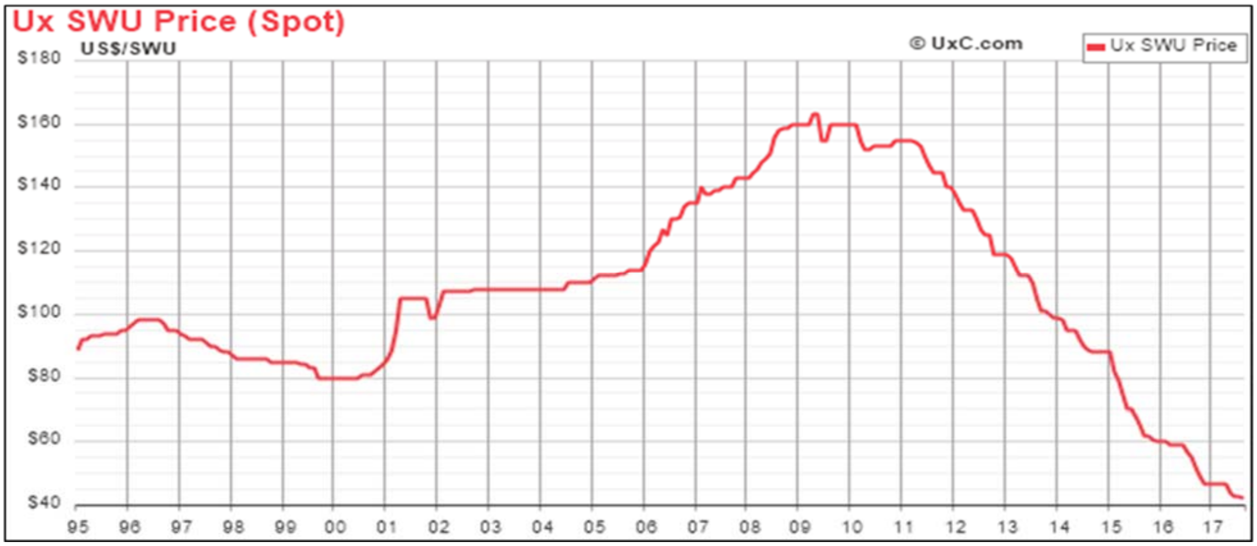


Figure C1–15 UxC SWU Spot Price, 1995-2017. Figure source: The Ux Consulting Company, LLC, http://www.uxc.com/. (Due to depressed market conditions, the June 26, 2017 UxC spot SWU price is $43/SWU)

As discussed in the *2009 Cost Basis Report* and (Schneider et al 2011), the primary impetus for lower long term SWU prices is the completion of the transition to centrifuge technology. Rothwell (Rothwell 2009) obtained construction cost data and estimates for five forthcoming enrichment facilities, three in the USA, one in France, and one in Brazil. Using these data with estimates of labor and other operating costs plus project-specific costs of capital, Rothwell derived a model of the levelized SWU cost, in $/SWU, as a function of these factors as well as plant capacity. Applying the model to existing plants, he obtained analogous replacement costs for the operating facilities.

Thus, SWU supply curves – plots of marginal SWU production cost versus quantity of SWU supplied – can be constructed from the results of (Rothwell 2009) with one plant excepted. Rothwell did not estimate the SWU cost at the forthcoming GE-Hitachi facility. This information continues to be covered by the veil of industrial secrecy. While the EIS for the facility (US NRC 2012) stated that the operator "considers laser-based technology to have lower operating costs and lower capital costs than … gas centrifuge technology," GE declined to publish capital or operating cost forecasts and no credible modern estimates could be found. Therefore, to complete the data set supplied by (Rothwell 2009), a 1982 estimate (Jensen et al 1982) of the SWU cost associated with the AVLIS laser-based enrichment technology will be used. Issues with laser tuning and power led to the cancellation of the US AVLIS program in 1999. The process and its feed form and equipment requirements are distinct from those of Silex. The AVLIS technology and cost estimate should not be viewed as surrogates for Silex. (Jensen et al 1982) projected AVLIS's cost at $30/SWU in 1982 dollars, $72/SWU once adjusted to 2012 dollars via the CPI[a].

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a. This cost should be considered as an upper bound for Silex. At the same time, once constructed the GE Silex plant will supply less than 5% of world enrichment capacity. Given the substantial investments being made in centrifuge plants in Europe, Russia and the US, and the probable long (40+ year) lifetime of these facilities, it appears certain that centrifuge technology will dominate the enrichment market for decades to come. Since this addendum forecasts the likely average SWU market

Figure C1–16 displays the 2010 and 2020 supply curves assembled from this data point and the (Rothwell 2009) results adjusted from 2008 to 2012 dollars using the CPI. Superimposing the 2020 WNA SWU demand forecasts[b] on the lower panel of Figure C1–16 permits a simple forecast of the market clearing SWU price. It is important to note that using the levelized SWU production cost of the marginal facility, i.e. the facility that meets the final unit of demand, to project prices is an idealization. It assumes that the market is free, competitive, international in scope, and frictionless (suppliers enter or exit without hindrance or impact on their costs). It further assumes that marketing decisions are made based on the all-in (operating plus amortized capital) cost of SWU, whereas short-term decisions may be driven by variable operating costs. But it retains value for predicting long term contract price trends, subject to considerations that will be discussed below. While the supply curves cannot be plotted past 2020 in view of the absence of company expansion or new build announcements, it is considered that the approach retains its ability to describe the overall structure of the market over the multi-decade lifetime of the upcoming generation of plants, even if they are subsequently expanded.

The lower panel of Figure C1–16 indicates that the 2020 market clearing SWU price might range from ca. $70/SWU (lower demand) to $100/SWU (higher demand). This assumes that all projects depicted in Table C1–1 come to fruition. If they do not, the price from the lower demand case would increase[c]. On the other hand, inflation-adjusted SWU prices have declined over the long term, and the ongoing evolution of the centrifuge technology will likely continue to push production costs downward. In Russian and European plants, a new generation of centrifuges has been developed every 5-10 years; a typical centrifuge remains in operation for 10-15 years before it is replaced. Thus the overall energy intensity (measured in kWh/SWU) of centrifuge plants has improved by a factor of around 6 since large-scale centrifuge enrichment began: from ca. 250 kWh/SWU in the late 1970s to less than 40 kWh/SWU at modern Urenco plants (Schneider et al 2011). Energy intensity is a driver of operating costs, although other centrifuge design and plant-specific factors make it difficult to directly correlate the SWU production cost at a facility to time. From this standpoint, then, the $70-100/SWU projection of the market-clearing price might **over predict** long-term prices.

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price over the coming decades, and plants using centrifuge technology will set the price, a precise forecast of Silex costs is not needed.

b. The WNA forecasts include demand for SWU from all sources, primary and secondary. They were each reduced by 4,000 kSWU/year to reflect the WNA projection of secondary (from HEU down blend) SWU supply in 2020.

c. If significant excess capacity does exist, large-scale upgrading (i.e., re-enrichment) of existing stocks of DU tails may resume. Through the 2000s, Tenex re-enriched DU held by Urenco and AREVA to NU levels, delivering approximately 5,000 tonnes of NU to European customers (OECD 2010a and OECD 2010b). As mentioned in Section C1-1, in 2012-13 USEC will re-enrich DOE-owned DU, although this decision was not market-driven. Upgrading of DU is SWU-intensive since the difference in U-235 assay between the feed stock and the so-called secondary tails is small. For instance, if tails assaying 0.35% U-235 are re-enriched with secondary tails at 0.20% (typical values selected from forecasts in [Schneider et al 2011], 12.4 SWU are required to produce 1 kg of LEU at 4.3% U-235 content. Only 7.3 SWU are needed if NU feed is used and tails are still taken to 0.20%. Worldwide, some 250,000 tonnes of DU assays at 0.30% U-235 or higher, and a shift toward upgrading of these stocks would act as a brake on declining SWU prices (see Refs. [Schneider et al 2011] [Schwartz et al 2012] for analysis).

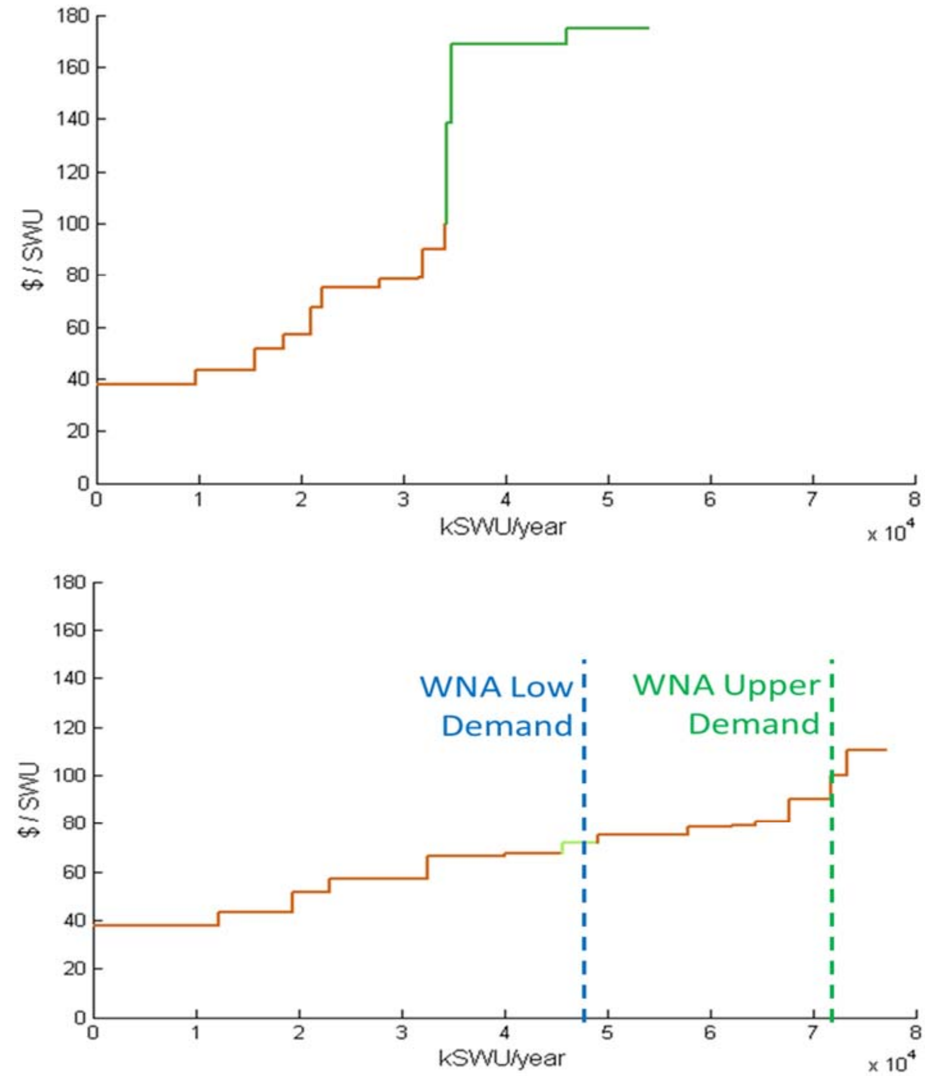


Figure C1–16 SWU supply curves, 2010 (top) and 2020 (bottom). Brown = centrifuge, Dark green = diffusion, light green = laser. Facilities of less than 500,000 SWU excluded.

One of the assumptions behind this simple model of price formation is that the market is competitive and free. Using a standard measure of the degree of concentration in a market, Rothwell showed that the enrichment market is strongly concentrated in the hands of three suppliers: Areva, Tenex and Urenco. Further, Rothwell observed that since Areva and Urenco are co-owners of their centrifuge manufacturer, Enrichment Technology Company Limited, they are incentivized to act in concert within the enrichment market (Rothwell 2009). In this case, the market could take on the characteristics of a duopoly led by Areva/Urenco and Tenex. Duopolists are endowed with market power, the ability to dictate the price of a product above its marginal production cost. By assuming competitiveness, the market-clearing price projection might **under predict** long-term prices.

Russian SWUs have had a significant effect upon European as well as US markets. Since the mid-1990s, Russia has been making available between 2.5 million and 4.0 million SWU per year to AREVA, URENCO, and others. These SWUs have consistently changed hands at lower than world market prices. Under the AREVA and URENCO contracts, over 100,000 tonnes of depleted uranium tails have been upgraded to natural uranium assay (Neely and Combs 2006). In late 2006, Minatom announced that contracts for this work would not be renewed once the current program is complete. It is likely that Russia perceives greater economic advantage in making this capacity available on the unrestricted world market. In fact, Russia has been using its excess SWU to enrich its own depleted uranium (DU) stockpiles. The 1.5% enriched blendstock used by Minatom to dilute HEU is in fact stripped from stored Russian tails. Russia uses almost as many SWU to produce this blendstock as would be needed to produce the LEU product from virgin uranium (Bunn 2008).

It is possible that some of the SWU capacity liberated by the lapsing of the Russian-European tails re-enrichment contracts may be deployed to enrich reprocessed uranium that was recovered from Japanese spent nuclear fuel (SNF) but still located in France and the UK. These uranium stocks, amounting to 6,400 tonnes, would be enriched in Russia as part of a larger deal involving natural uranium extraction and enrichment from mines in Kazakhstan in which Japanese companies hold a stake. The Japanese newspaper Yomiuri Shimbun reported that the negotiations are in their “final stage,” (World Nuclear News 2007), but no particulars regarding the terms of the deal are yet available.

## C1-6.1 Time Series Analysis of Uranium Enrichment Market

Module A of the CBR contains causal and time series analysis in order to generate forecasts of uranium prices. Both approaches produce forecast estimtates within a similar range. In this moduel, time series analysis is conducted to form a basis of price estimates for SWU. Whereas historic price data on uranium can be accessed for a lenththly time series (see Module A), price data for SWU are more scarce. Because of this, the analyst must rely on what data are available for SWU, and Ux Consulting is a primary source for these data. Figure C1–15 shows the SWU price data used in the analysis below. The schedule of data is not available so instead, the anlayst used the plot in Figure C1–15 to generate a time series. This data sereis is recreated below in Figure C1–17 in green, the current value of the series. The orange plot is of the same series after escalating the data to constant 2017 values using the escalation method outlined in Chapter 7 of the CBR.

Figure C1–17 shows two contrasting trends. For the current values (series in green), an upward trend in prices appears from 1995 through 2010. On the other hand, the constant value (in orange) show essentially a downward trend beginning in 1995. Two observable exceptions are in 2004 and in 2010 when SWU prices spiked for a short time. Otherwise, in real terms, SWU prices have been declining for the past 22 years. Similar to the time series analysis in Module A, SWU prices are forecasted using historical data up through 2016 in constant 2017 dollars. That is, the historical series represented in orange are the seed data used for the time series analysis and forecast of SWU prices.

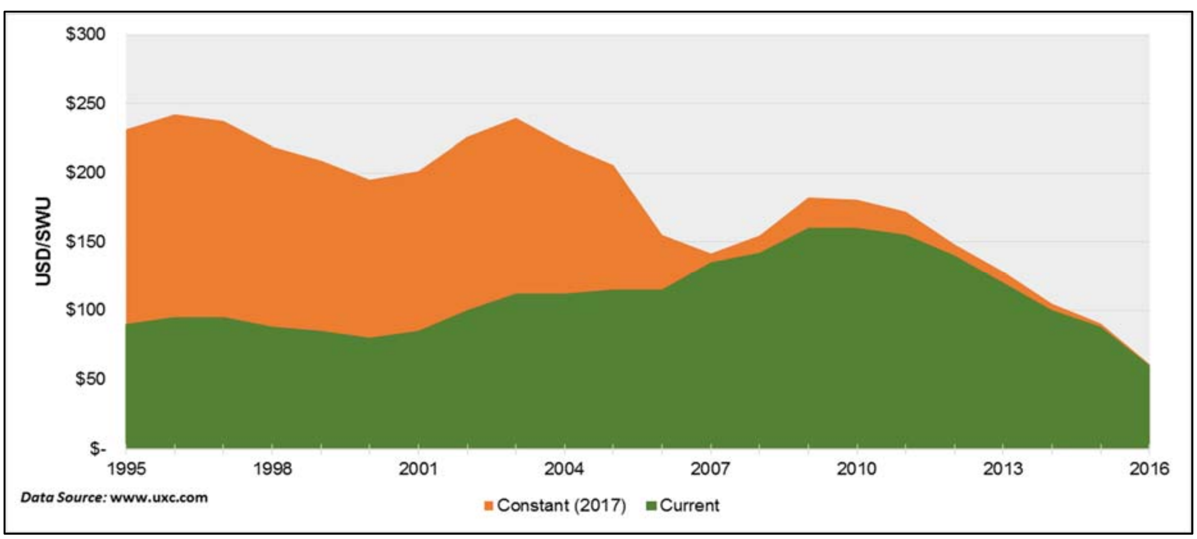


Figure C1–17 SWU Prices in constant and current dollars annually.

In order to use the data series, SWU prices in constant dollars from 1995 to 2016, to forecast SWU prices it must be stationary. Based on the autocorrelation and partial autocorrelation functions, statistical testing indicates that the series is not stationary. Taking first differences and taking the logarithmic values of the data series results in a stationary series. Once stationary, the data can be fitted with a time series process.

Figure C1–18 shows the fitted model, the historical path, and the sample path. The historical path, the blue line in the figure, shows the actual data series from Figure C1–15. These data are best fit using a moving average process over one period. The software @Risk fits the data with many time series and stochastic processes then allows the analyst to compare model fits using the Akaike Information Criterion. Based on fitting the data to a model, the SWU prices data series is best represented with a moving average process, MA(1), where the average is computed over one period. Further the Mean Absolute Percentage Error (see Module A) for the forecast is 20.99, which indicates the forecast does a reasonably good job at reproducing the historical data series.

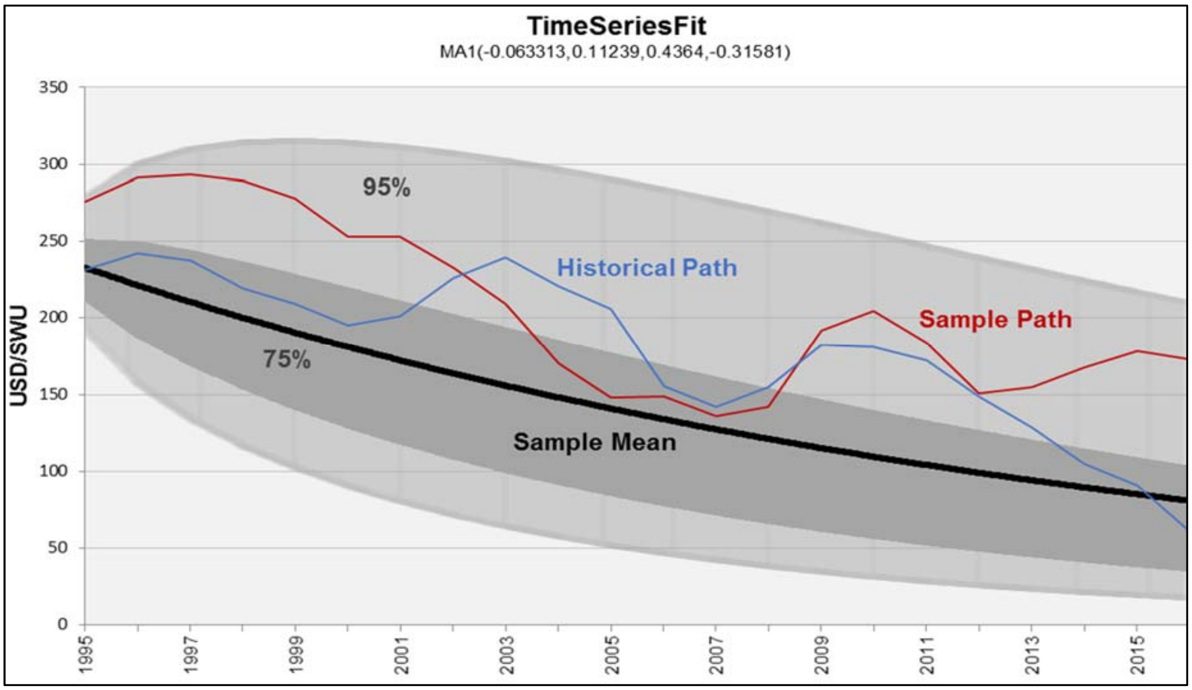

Figure C1–18 Comparing predictions using time series fitted model with historical data.

Using the fitted model and the SWU price of 1995, the MA(1) model produces a sample path indicated in red. Because the MA(1) is a stochastic process, the sample path could take many different routes based on the model random process. The black line indicates the mean of the possibilities and the light gray areas indicate the 95% confidence interval in which simulated observations occurred. The dark gray indicates the 75% confidence interval. The MA(1) becomes the model used to forecast SWU prices out to the end of the century in year 2100.

The MA(1) becomes the model used to forecast SWU prices. Figure C1–19 shows a price forecast through the end of the century. The mean of the observations is represented by the solid blue line in the center of the figure. It steadily decreases through the end of the century because of the downward trend that populates the time series process in the historical data. Because the simulation produces a distribution of possibilities in each year, additional statistics about the forecast are provided. The 90% and 10% lines indicate where 80% of the observed values in simulation resulted. The average value for the 10% line is $5.92 and for the 90% line is $19.84. The mean value, the solid blue line, across the simulation is $12.02.

The mode, the red line shown with variation, plots the mode from the distribution in each year. The most frequently occurring value in a distribution, the mode is a useful statistic to answer the question of what is the "most likely" value to expect in a given year. While the mean shows a decreasing trend, the mode illustrates what the volatility in SWU prices might look like as they decrease through the century.

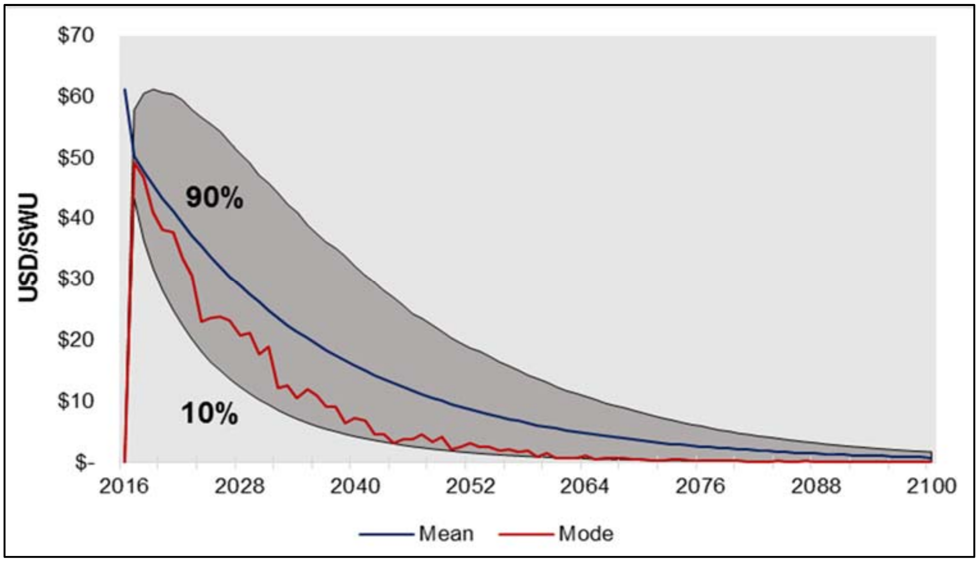


Figure C1–19 SWU price forecast using one-period moving average time series model based on historical SWU prices 1995 – 2016.

Coupled with Figure C1–19, Table C1–6 provides statistics form discrete intervals with in the simulation. Representing possibilities for SWU prices 10 years out, 25 years out, 50 years out, and through the end of the century, the table provides the statistics that are illustrated in Figure C1–19. The table show statistics by year in two formats, "In Year" and "Up to Year." The In Year statistics come from the distribution of possibilities for the year indicated. The Up To Year statistics represent what one might expect leading up to the year indicated. Notice the tighter confidence intervals and smaller standard deviation in the Up To Year statistics. This results because of the law of central tendency. Because the distributions from each year are averaged to compute the Up to Year statistics, the resulting distribution is more narrow (i.e. has less uncertainty) than the distribution of a single year.

Table C1–6 Summary statistics of SWU price forecast by year and up to year.

| Year(s) | Mean | Mode | Std Dev | 10% | 90% |
|---|---|---|---|---|---|
| In 2027 | $30.42 | $20.64 | $17.00 | $13.56 | $51.92 |
| Up to 2027 | $39.66 | $36.54 | $12.19 | $26.35 | $55.63 |
| In 2042 | $14.24 | $3.90 | $13.45 | $3.66 | $29.12 |
| Up to 2042 | $28.76 | $23.49 | $12.39 | $16.24 | $44.26 |
| In 2067 | $4.07 | $0.54 | $6.67 | $0.49 | $9.02 |
| Up to 2067 | $18.56 | $12.58 | $9.89 | $9.48 | $30.30 |
| In 2100 | $0.77 | $0.05 | $1.93 | $0.04 | $1.74 |
| Up to 2100 | $12.02 | $8.03 | $6.95 | $5.92 | $19.84 |

The analysis produced using the historical data on SWU prices generates a forecast of prices (Figure C1–19 and Table C1–6) that is significantly different from those recommended in previous versions of the CBR. Previous expectations for SWU prices are shown in Table C1–6. This disparity suggests a need for in-depth analysis of the market for enrichment. Such analysis has been done previously and supports earlier SWU price recommendations from the CBR. The time series analysis presented here implies that factors in the enrichment market have changed considerably since the time of the last in-depth inquiry.

A possible explanation for this dramatic shift is the recently completed technical revolution. With the technology replacement of the Georges Besse enrichment facility of gaseous diffusion to Georges Besse II with centrifuge. Now that this replacement facility is online and ramped to full capacity as of 2016, it is likely the case that greater capacity at a lower price is contributing to lower SWU prices. Coupled with the reduction in demand from Japan, these could be causes for depressed SWU prices observed in recent history. These market conditions underscore the need for in-depth analysis of the enrichment market. It is very likely the case that enrichment market is in a transition to a new, lower phase of SWU prices. Informed by the time series analysis in this update, a conclusion that one can take is that SWU prices are adjusting down. Greater analysis will inform drivers behind the story the numbers illustrate. For these reasons, the time series presented here is not represented in the recommended prices in the What it Takes Table.

## C1-6.2 2016 Spot Check on Market for Uranium Enrichment

Enrichment prices have also been following the same basic pattern as uranium ore discussed above, with lower values of $80-100/SWU prior to 2008 followed by rising prices to $160/SWU in 2009. The prices held in the $150-160/SWU level until Fukushima in 2011, and have declined steadily since then to $55/SWU as of the end of August, 2016. While the pattern is similar, suggesting the same drivers of optimism over the nuclear renaissance followed by post-Fukushima oversupply, there are additional contributing factors.

One factor is the completion of the conversion to centrifuge enrichment with the retirement of the large gaseous diffusion plants in the U.S. and France. Georges Besse (France) ended operations in 2012 while Paducah (U.S.) ended operations in 2013. Both were large capacity facilities with high operating costs, which provided support to the SWU price as essentially dictated by the marginal producers that supply the last segment of demand. With their retirement, prices dropped to reflect the more efficient production costs of the centrifuge facilities (including George Besse II). This impact was predicted in (Rothwell 2009a), with the predicted drop from the $160/SWU level to a new level around $100/SWU (in 2009 dollars). The post-Fukushima oversupply compounded the drop, which may not yet be over.

SWU spot prices as of 2016 at $55 are below the low end of the recommended price range in the 2015 CBR (low $89, mode $116, high $142, mean $116/SWU) – See Figure C1–20. As long as a supply/demand imbalance exists, prices could go lower, especially since the variable cost of production with centrifuges is quite low and centrifuge equipment is designed to run continuously (for decades) rather than be cycled up and down. However, several market adjustments are occurring. On the supply side, new plants in North America have been cancelled (Piketon, OH) or postponed indefinitely (Idaho Falls, ID, Wilmington, NC) but some expansion of plants in China may be occurring. On the demand side there is the continued construction of new reactors in Asia and the Middle East and anticipation for additional reactors to restart in Japan. At this point, no change in pricing is recommended until the near-term impact of reactors in Japan is resolved. The current price mode of $116/SWU reflects the price predicted by Rothwell based on a market using centrifuge production costs, escalated to 2015 dollars.

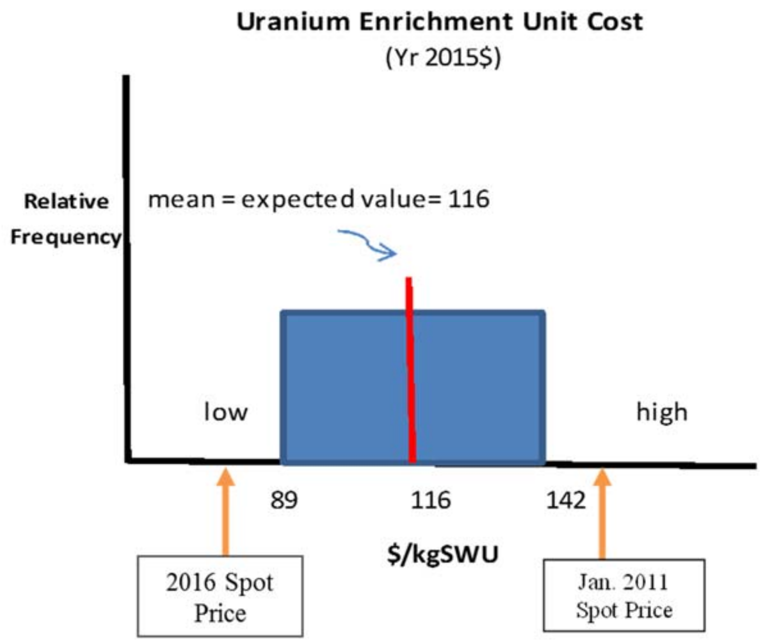


Figure C1–20 Separative Work Unit Cost Range in 2015 CBR showing current and pre-Fukushima spot prices

Using the price ranges for uranium, conversion, and SWUs, an optimal tails assay (% U-235 in the depleted U stream from an enrichment plant) can be determined to minimize the total front end fuel cycle cost for low enriched uranium (LEU). A tool is available on-line (UxC tool) to perform this calculation. Note that secondary considerations such as loss factors, waste disposal costs such as DU disposition, etc., are typically not included in a cost analysis. These secondary considerations are discussed in (WISE 2009a).

Using the UxC calculation, the optimal tails enrichment level is 0.25% U-235 when using the "mode" values for U, conversion and SWU, while it is 0.2% U-235 when using current market prices.

## C1-6.3 Enrichment of Reprocessed Uranium

Prices for reenrichment of depleted uranium hexafluoride would be the same as prices for identical services involving natural uranium. The situation for reprocessed uranium (RU) is more complex. Although commercial RU enrichment is not presently taking place (subject to change in the near term in view of the Russian-Japanese negotiations), the U.S., Russia, and France have enriched RU within their facilities. Russia and France's supplies are in significant quantities. The U.S. does not presently hold large stocks of RU.

The most recent major study of RU enrichment in the U.S. took place in 1993 (Michaels and Welch 1993). Given the availability of RU stocks, the option has received more frequent attention in Europe (a Russian study [International Business Relations Corporation 2006] was issued in 2006). Given that the latter report is proprietary, the conclusions presented below are drawn from the earlier U.S. study. The Department of Energy (DOE) is presently obligated to accept RU for enrichment, provided the source uranium was originally enriched in a DOE facility and it meets certain purity standards. DOE reserves the right to apply an additional "service charge," which has historically been nominal—up to $10 per kilogram of RU feed or about a 10% surcharge per SWU when the separative work is computed according to the traditional two-component formula. The service charge is in fact based upon the additional separative work requirements to enrich RU feed to a specified U-235 content given the presence of U-236. Indeed, to ensure that the tails from the RU enrichment process can be stored and disposed in the same manner as traditional DU, it is advantageous to pursue one of the following:

- Blending of RU feedstock with natural uranium (NU) to decrease the U-232 and U-236 concentrations. This strategy offers the further advantage of reducing the level of over-enrichment required to compensate for the negative effect of U-236 on the neutron economy of a reactor.
- Blending of RU with HEU or alternatively LEU having greater than 5% enrichment. This option would obviate the need to pass any RU through an enrichment cascade, but like RU use as a diluent in mixed oxide or fast reactor fuel, it may not be sufficient to balance the rate at which RU is recycled with the rate at which it is produced.
- Employment of a secondary cascade to produce a second tails stream that is highly concentrated in U-232. This small amount of material would require some decades of storage before becoming disposable in the same fashion as traditional DU.

In any case, since there is no indication that Russia imposes more than a nominal surcharge for enrichment services involving RU and since the DOE charge is also nominal, the SWU price estimates given in this section would also be valid for RU, *given that the RU meets purity standards* and that the separative work for the multicomponent stream is calculated according to the methodology given in the 1993 ORNL report (Michaels and Welch 1993). If the simpler two-component (U-235 and U-238) equation is used to calculate the SWU, a 10% surcharge should be assessed to the SWU cost as a first approximation.

Decontamination and Decommissioning (D&D) is the area in which enrichment of RU would be expected to most impact costs. (RU reenrichment exposes the cascades to small but significant amounts of U-232 and daughters, some trace transuranics, and some troublesome trace fission products such as technicium-99m.) A great deal of uncertainty surrounds the correlation between RU enrichment and D&D costs for the three U.S. enrichment facilities. The Uranium Enrichment Decontamination and Decommissioning Fund was established by the 1992 Energy Policy Act. This fund was to be paid into between 1992 and 2007 by government appropriations and utilities, with the utility portion reflecting previous purchase of SWU from government-owned facilities. In addition to D&D costs, the fund is also intended to defray remedial cleanup activities, waste management, plant surveillance and maintenance, and reimbursement to active uranium and thorium processing facilities to defray their own decontamination and cleanup costs. Therefore, it is difficult to identify from the fund balance that portion of the costs that are attributable to RU enrichment.

The most substantial additional expenses that adhere to RU enrichment are therefore purification and tails disposal (see Module K). Effective removal of fission products, especially Tc-99, is necessary prior to enrichment or disposal. Both of these issues are also complicated by the presence of the isotope U-232. Although U-232 ($T_{1/2}$ = 68.9 yr) is present in RU at levels of a few parts per $10^7$ atoms, Th-228, and other daughters in its chain that undergo particularly energetic decays lead this parent isotope to be the dominant contributor to the RU dose field. Given that these daughters are removed from the uranium stream at the time of separation, it is advantageous to enrich RU as quickly as possible to avoid a costly secondary purification step. Indeed, the dose rate from RU immediately following its separation is nearly the same as that of NU. One year after separation, the RU dose rate increases to almost ten times that of NU and its decay power exhibits an even more substantial increase; the radiation field from RU peaks about 10 years after separation. Therefore, it seems essential to enrich the RU within a few months of its separation.

If quick re-enrichment is not possible, or if the original separation process does not sufficiently extract certain fission products and actinides, additional “polishing” of the RU would be required. A number of polishing processes have been proposed. While PUREX or a similar aqueous process could be employed, given the low contaminant concentrations, other methods offering considerably less complexity and expense can be pursued. One of these is fluoride volatility purification (high-purity separation of uranium fluorides from fluorides of many fission products and actinides). Uranium fluorides become volatile at significantly lower temperatures than other fluoride compounds; none of the noble metal fluorides become gaseous at a temperature within 30 K of the $UF_6$ boiling point. Indeed, this purification process is already employed at the Metropolis Works and other U fluorination facilities, and the cost of purifying RU in this fashion would be similar to the cost of conversion. See Module K2 for further discussion of RU polishing and its cost.

## C1-7. DATA LIMITATIONS

There are many factors with impact on the enrichment demand. See Section C1-4 for details. Real time costs are not reported because of the highly competitive nature of the tight supply-demand scenario, which at this point is nearly balanced.

Modelers and forecasters must view the total uranium supply picture and consider the closer relationship between the price of natural uranium and enrichment as utilities try to optimize the total front-end of the fuel cycle. While enrichment currently represents between 30 and 40% of the cost of fuel, short-term fluctuations should have only a moderate impact on the overall fuel cycle costs. When a closed fuel cycle is considered, its impact will be dwarfed by the reprocessing and fuel fabrication expenses.

As centrifuge technology replaces diffusion, assuming long-term supply-demand equilibrium with open markets, its lower production costs should translate into lower SWU prices. A dramatic drop in SWU prices is not expected for two reasons. First, since centrifuge plants are modular, producers can expand capacity incrementally and relatively quickly, avoiding creation of a persistent supply glut. Second, the SWU market is not fully competitive in the sense that enrichers do not offer fully flexible contract terms. For example, the cost-minimizing process of tails enrichment optimization, while easy to carry out in paper, is not generally an option in present-day contracts which stipulate a fixed tails assay for their duration.

## C1-8. COST SUMMARIES

This section presents low, high and nominal enrichment price forecasts. Module C1, along with other front-end modules, addresses an industry with a well-developed market. Therefore, although the forecasts presented here are labeled ‘costs’ for consistency with the format used across this report, they should be interpreted as estimates of the long-term average SWU contract price. See the price data section in the front of this addendum for further discussion on the use of price data in the Cost Basis forecasts.

The **nominal** estimate, $100/SWU, assumes that capacity remains nearly fully utilized after the transition to centrifuge technology is complete. This is the case for the WNA upper-demand scenario outlined in Section C1-2, and it would likely also be true for the lower-demand scenario as some planned construction is abandoned and other capacity is shifted to DU tails upgrading. The projection is lower than current spot market prices because SWU production costs at all centrifuge facilities are evidently lower than the 2012 price of $130/SWU. SWU production costs will continue to decline in the future thanks to ongoing development of new generations of centrifuge equipment, possibly accelerated by the entrance of Silex. On the other hand, the concentrated nature of the market, dominated by two to three suppliers, will likely prevent prices from falling as far as declining production costs imply they should. Here the balance of these effects is considered to result in prices remaining near the contemporary production cost of the higher-cost players in the market.

The **low cost** estimate, $70/SWU, hypothesizes that significant capacity in excess of demand will be built. Some of this capacity might be engaged, with marginal profitability, in the upgrading of DU tails stockpiles. Costlier to run facilities might be pushed out of the market entirely over time. Further, the low estimate considers that the market will not exhibit strong duopolistic characteristics, but rather function as a close approximation to a competitive market.

The **high cost** estimate, \$120/SWU, assumes that installed capacity is fully utilized, as is the case for the nominal estimate. It may come about if uranium prices trend higher, since elevated uranium prices provide an ongoing incentive for utilities to substitute SWU usage for natural uranium purchase. It may also come about if conditions of effective duopoly prevail and the major suppliers are able to exert a considerable degree of market power. \$120/SWU was chosen because it reflects the levelized SWU cost projected by (Rothwell 2009) for the costliest of the proposed centrifuge plants, one that is independent of the duopolists. If the price rises to this level, independent players are thus considered to be in a position to profitably enter the market, effectively capping prices.

The module cost information is summarized in the WIT cost summary in Table C1– 7.

Table C1– 7 “What-it-takes” (WIT) Table (2012\$).

| Reference Cost(s) Based on Reference Capacity | Low Cost | High Cost | Mean/Expected Cost |
|---|---|---|---|
| ***2009 CBR Values in 2009\$*** | | | |
| *\$110/SWU* | *\$85/SWU* | *\$135/SWU* | *\$110/SWU* |
| **2012 BR Addendum Values** | | | |
| \$100/SWU | \$70/SWU | \$120/SWU | \$97/SWU |
| ***2009 CBR Values Escalated by 5% to 2015\$*** | | | |
| *\$116/SWU* | *\$89/SWU* | *\$142/SWU* | *\$116/SWU* |
| ***2009 CBR Values Escalated by 14% to 2017\$ per Escalation Table in Main 2017 CBR*** | | | |
| \$125/SWU | \$97/SWU | \$154/SWU | \$125/SWU |

A uniform distribution was chosen to reflect SWU prices. See section C1-9 for discussion. The uniform distribution based on the costs in the WIT table is shown in Figure C1–21.

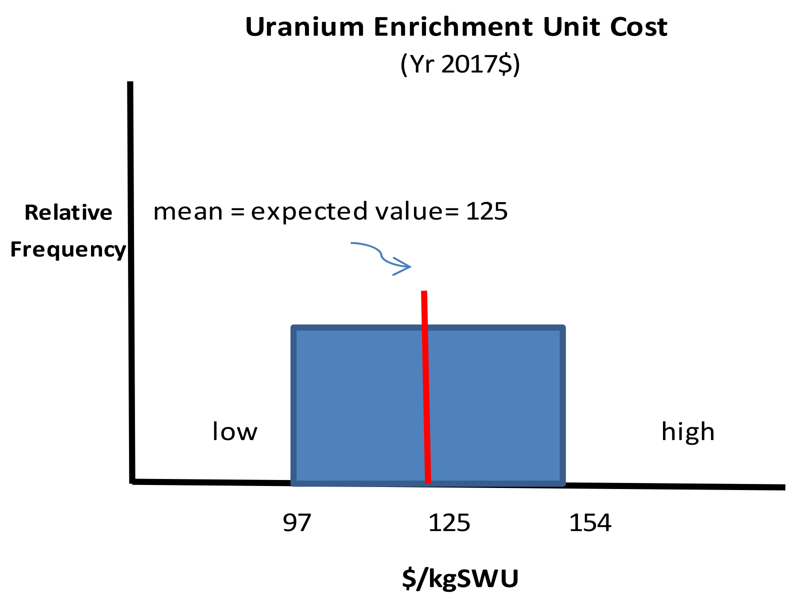


Figure C1–21 Enrichment estimated cost frequency distribution.

# C1-9. SENSITIVITY AND UNCERTAINTY ANALYSIS

SWU is a service and as such is subject to volatility not seen in largely noncompetitive back end processes such as reprocessing and repository disposal. It is important to reflect this volatility in the proposed long-term price distribution, so that uncertainties in future SWU prices are properly captured. Figure C1-18 is a histogram of the inflation-adjusted quarterly average SWU price shown in Figure C1-19.

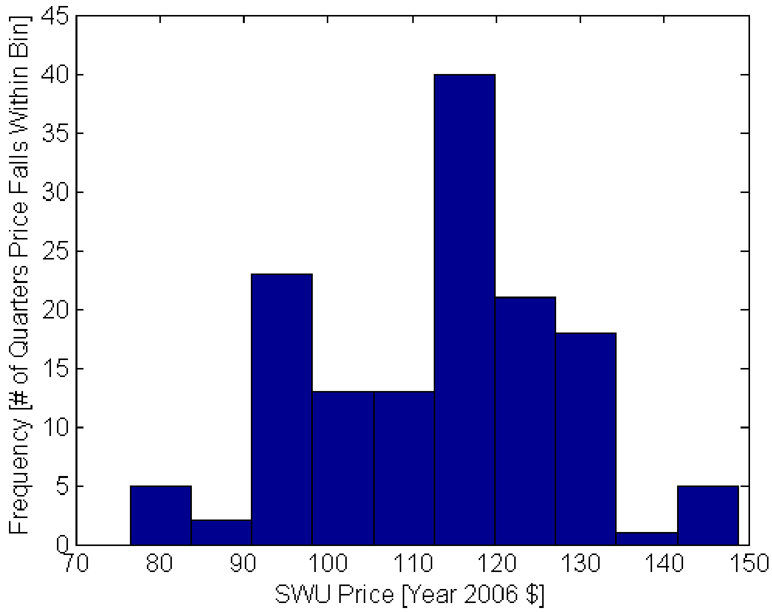


Figure C1–22 Histogram of quarterly SWU prices, 1972–2006.

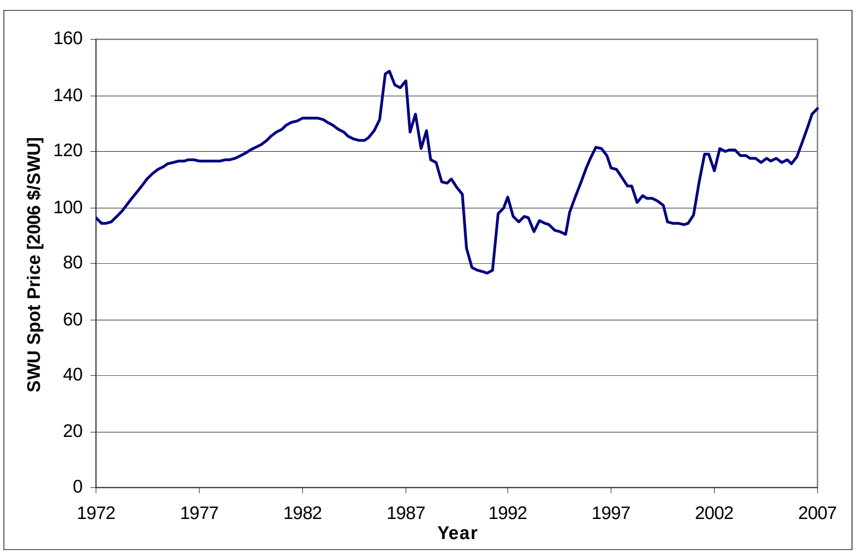


Figure C1–23 Historical SWU price (UxC spot post-1986), adjusted for inflation.

Table C1–8 summarizes the statistical parameters of the historical SWU price along with those of two proposed future price distributions. Both of these have lower and upper bounds of $80 and $130 per SWU. One proposed distribution is triangular, like those employed to describe costs associated with many other modules; it is also symmetric, with the likeliest price chosen to be $105 per SWU. The second option is a uniform distribution, with all prices between $80 and $130 being equally likely. The triangular distribution shows a smaller variance than does the historical SWU price data; the uniform distribution matches well in this area.

Therefore, the uniform distribution, with its implication that low and elevated SWU prices are equally likely even over the long term, appears more able to replicate uncertainties in this price. It is adopted as the reference distribution for this module.

Table C1–8 Statistics of historical quarterly SWU price distribution versus proposed distribution (2006 dollars).

| | Historical ($/SWU) | $80–130 ($/SWU) Triangular Symmetric | Proposed: $80–130 ($/SWU) Uniform |
|---|---|---|---|
| Mean | 113 | 105 | 105 |
| Median | 116 | 105 | 105 |
| Standard Deviation | 14.9 | 9.8 | 14.9 |

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# Module C2

# Highly Enriched Uranium Blend-Down

# Module C2
# Highly Enriched Uranium Blend-down

## C2-1. BASIC INFORMATION

Module C2 discusses the former use of U.S. and Russian government-owned highly enriched uranium (HEU) blended down as a secondary supply to meet demand for low-enriched uranium (LEU). The introduction of such government weapons-origin LEU has a direct impact on the uranium supply chain by reducing the need for newly mined uranium, conversion capability, and enrichment services. This impact was anticipated, and the two governments agreed to control such addition into the LEU supply so as to have minimal impact on the front end fuel cycle industries.

After the end of the Cold War, nonproliferation considerations made it imperative that safe and economical means be found to disposition stockpiles of surplus HEU (and other nuclear materials) from the U.S. and Russian weapons complexes. Because of the quick dissolution of the Soviet Union, the security of HEU in Russia became the paramount issue. In the mid-1990s, a program was initiated under which the west would receive and purchase $LEUF_6$ from Russia. $LEUF_6$ is made by blending converted (U-metal to UF6) Russian HEU with Russian slightly enriched uranium as UF6. This bilateral U.S.-Russian “Megatons to Megawatts” program agreed to the blend-down of 500 MTU of Russian HEU with Russia receiving market value for the separative work units (SWUs) and natural uranium feed content for the LEU produced by blending.

The U.S. private corporation United States Enrichment Corporation (USEC) acts as the U.S. agent for enrichment sales to U.S. utility customers, and Techsnabexport (known as TENEX) acts as Russia’s executive agent for sales to USEC. The U.S. agreed to purchase over a 20-year period (1994–2013), 500 metric tons (MT) of HEU (~90% U-235) from Russian weapons down blended to $LEU_6$ (4.5% U-235). The HEU is down blended in facilities at Seversk, Zelenogorsk, and Novouralsk. USEC receives the equivalent of about 30 MT/yr of HEU in the form of $LEU_6$ (~5% U-235) derived from blend-down of Russian HEU for sale and distribution to the U.S. utility market. In return for the LEU procured from Russia at an agreed upon market price, USEC returns to TENEX natural uranium as uranium hexafluoride ($UF_6$). This is equivalent to the natural uranium and conversion service that was incorporated into the down-blended HEU, effectively only procuring the enrichment services SWUs contained in the LEU. USEC uses the $UF_6$ to supply utility customers in the U.S. This secondary supply of LEU, therefore, effectively represents about 5.5 million SWU annually to the U.S. market. In most years of this decade, the 870 MT of LEU delivered annually to the U.S. from this program supplied approximately 40% to 50% of the nuclear power used in the U.S. and approximately 10% of overall U.S. electricity production. As of June 30, 2009, 367 metric tons of bomb-grade HEU have been recycled into 10,621 metric tons of LEU, equivalent to 14,686 nuclear warheads eliminated.

The natural assay $UF_6$ that is received by TENEX is marketed through an HEU Feed Deal Agreement to a consortium of Cameco, COGEMA (AREVA), and RWE NUKEM. The remaining $UF_6$ that is not purchased can be returned to Russia and placed in an inventory monitored by the U.S. Department of Energy (DOE). Each year TENEX is permitted to withdraw 7,000 lb from the approximately 44 MT of monitored inventory for use in further downblending or delivery into existing contracts in Russia and the former Soviet-bloc states.

In July 2006, the Russian Federal Atomic Energy Agency announced that Megatons to Megawatts would not be renewed past its 2013 expiration date. While it is possible that Russian downblending activities will continue, it appears that Russia views direct control over the marketing of the LEU product to be advantageous. It is known that they still have hundreds of metric tons of HEU in surplus for their military needs. Although this development was not unexpected, it is now certain that domestic utilities will need to look elsewhere to secure the 40–50% of their annual requirements that are currently being served by Megatons to Megawatts.

Likely, the 1992 USEC-TENEX agreement will be amended such that Russia (Tenex) can directly compete for up to 25% of the U.S. enrichment market after 2013. The SWUs produced may not necessarily come from blend-down in Russia. Russia has plenty of gas centrifuge enrichment capacity available for direct production of LEU from either tails or natural uranium feedstocks. This agreement is to stay in force until 2020, at which point Russia will no longer have a marketing cap imposed. These constraints are required to protect the U.S. front-end fuel cycle industries (mining, milling conversion, and enrichment) from SWU "dumping" because of Russia's ability to undercut the pricing of all competitors. This issue of international SWU marketing is discussed in a comprehensive paper by Matthew Bunn (Bunn 2008).

Figure C2-1 is a schematic of the U.S.-Russian Megatons to Megawatts program.

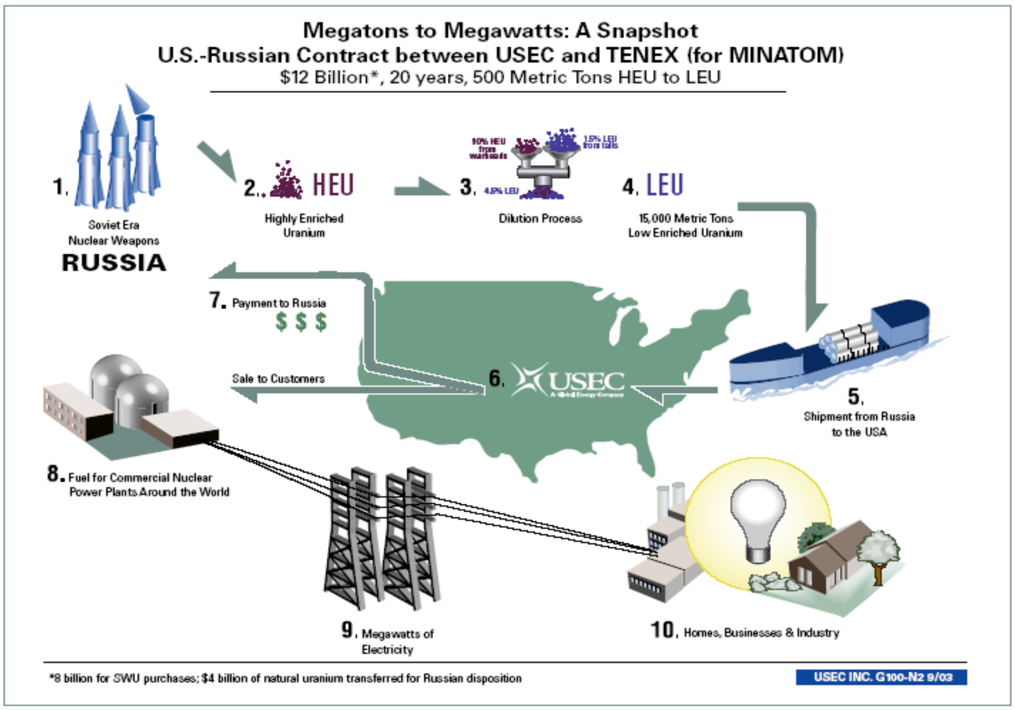


Figure C2-1. Megatons to Megawatts program (USEC 2001).

The U.S. has its own version of the Megatons to Megawatts program declaring an excess of 174.3 tons of HEU from the weapons program. This HEU has a U-235 content from 50 to 90+% with various amounts of impurities. Some of this material was of sufficient quality to be down blended at USEC's Portsmouth Plant (14.2 MT HEU) with additional downblending in progress at BWX Technologies Inc. in Lynchburg, Virginia (46.6 MT HEU). These two down-blending campaigns were completed in July 1998 and September 2006, respectively. Some of the U.S. Government "off-spec" HEU (reprocessed HEU with U-236 and slight fission product/transuranic contamination) has been processed and blended down under the BLEU (Blended Low Enriched Uranium) program. The material (~39 MT HEU) is decontaminated at the Savannah River Site (SRS) in Aiken, South Carolina, and shipped to Nuclear Fuel Services in Erwin, Tennessee, for blend-down to LEU and refabrication by AREVA for use in Tennessee Valley Authority reactors. (The blending and refabrication of this material for use in LWRs is discussed in Module D1-1.) Approximately 120 MT HEU remaining in DOE inventory represents a reserve of about 21,000 MT of natural uranium equivalent, roughly 1 year's supply for the domestic reactor fleet at current consumption rates.

Up until very recently, the down-blended LEU has purposely not been made available for sale in the U.S. to avoid a significant negative impact on the uranium supply and conversion vendors (see Section C2-9). The U.S. DOE has recently procured a contractor to expedite the blend-down of surplus Defense program HEU to LEU. The contractor will be allowed to keep an agreed amount of the blended material as compensation for their effort and which can be sold to nuclear utilities. Nuclear Fuel Services of Erwin, Tennessee, a recently purchased subsidiary of Babcock and Wilcox, is the selected contractor to DOE/NNSA for this program (NFS 2008). DOE will continue to control the entry of the HEU to LEU into the market. In fact, the probable DOE strategy calls for its sales from all sources to not exceed 10% of the annual domestic requirements (i.e., about 2000 MT natural uranium equivalent per year). While the bulk of DOE sales over the next decade are expected to come from downblended HEU, off-spec and otherwise, the HEU represents only a minority of DOE's total reserve of about 52,000 MT natural uranium equivalent. The remainder of the DOE inventory is in the form of $UF_6$; while most of this is unenriched natural uranium, part (9000 MT natural uranium equivalent) is termed "depleted uranium of economic value." The assays in this stockpile are variable but never less than 0.4% U-235. The U.S. DOE recently issued a "Management Plan" for the disposition of this material. (DOE 2008)

## C2-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

**Russian HEU to LEU.** The product received by USEC is $EUF_6$ in small $UF_6$ cylinders of 4–5% U-235 content shipped from St. Petersburg, Russia, to a U.S. port and eventually DOE's Portsmouth or Paducah sites, which are leased by USEC. At theseUS sites, it can be further blended from 5.0% U-235 to the light-water reactor utility's exact U-235 assays before shipment to a fuel fabricator. Under USEC's arrangement it is receiving only SWU from Russia, not uranium. USEC is obliged to return the uranium content of the $EUF_6$ to Russia. Typically the USEC sells Russian LEU to their customers and returns to the Russians natural uranium that those customers gave USEC to enrich.[d]

The conversion of Russian nuclear weapons takes place at several locations. It begins with the removal of the warheads and their HEU metal components from strategic and tactical nuclear missiles**.** The HEU warhead components are machined into metal shavings. The shavings are then heated and converted to an HEU oxide, and any contaminants are chemically removed. The HEU oxide is converted to highly enriched $UF_6$, a compound that becomes a gas when heated. The highly enriched $UF_6$ is introduced into a gaseous process stream. There, it mixes with other material and is diluted to less than 5% concentration of the fissionable U-235 isotope. The now low-enriched $UF_6$ fuel is checked to ensure the product meets commercial specifications and is then transferred to 2.5-ton steel cylinders. The uranium fuel is enclosed in shipping containers and sent to a collection point in St. Petersburg. USEC takes possession of the fuel containers in St. Petersburg and they are shipped to USEC's facilities in the U.S. (originally the Portsmouth plant but now the Paducah plant). The LEU is tested again to ensure that it meets appropriate commercial and customer specifications. If necessary, the enrichment level of the uranium fuel can be further adjusted at Paducah to meet utility customers' needs. Based on customer instructions, USEC ships the LEU fuel to fabricators (Global Nuclear Fuel, Framatome, or Westinghouse), who convert the LEU into uranium oxide pellets and fabricate them into fuel assemblies. The assemblies are then shipped to USEC utility customers as a source of fuel for their nuclear reactors.

**U.S. HEU to LEU.** Unlike conversion facilities in the Russian Federation, U.S. facilities must convert HEU metal into uranyl nitrate hexahydrate (UNH). For project BLEU, which uses previously irradiated SRS(Savannah River Site) uranium the blended UNH product is delivered to fuel fabricators where it can be further converted to uranium oxide powder and pelletized for use in fuel rods. At the SRS,

d. USECs 2006 K-10 SEC filing.

off-specification material from weapons production was dissolved and processed through H Canyon (a large chemical fuel reprocessing plant) to remove impurities, blended with natural uranium supplied by industry, and shipped as a UNH solution to Nuclear Fuel Services in Erwin, Tennessee. Nuclear Fuel Services will also eventually convert HEU metal and unirradiated uranium-aluminum alloy into uranyl nitrate solutions as well. The UNH solutions from SRS and Nuclear Fuel Services (NFS) will be converted by NFS/AREVA to LEU oxide powder. The oxide will be shipped to Richland, Washington, where it will be prepared and pressed into fuel pellets and built into fuel assemblies by Framatome Advanced Nuclear Products to be used in Tennessee Valley Authority reactors. The new blend-down program being undertaken by NFS will utilize “virgin” or unirradiated HEU surplus to defense programs. The uranium processing methodologies will be similar, with the difference that the feedstock should have fewer impurities.

## C2-3. PICTURES AND DIAGRAMS

Figures C2-2 and C2-3 show simplified flow diagrams for the Russian and U.S. processes “currently” being deployed to blend down excess weapons HEU material to LEU for use in commercial reactors.

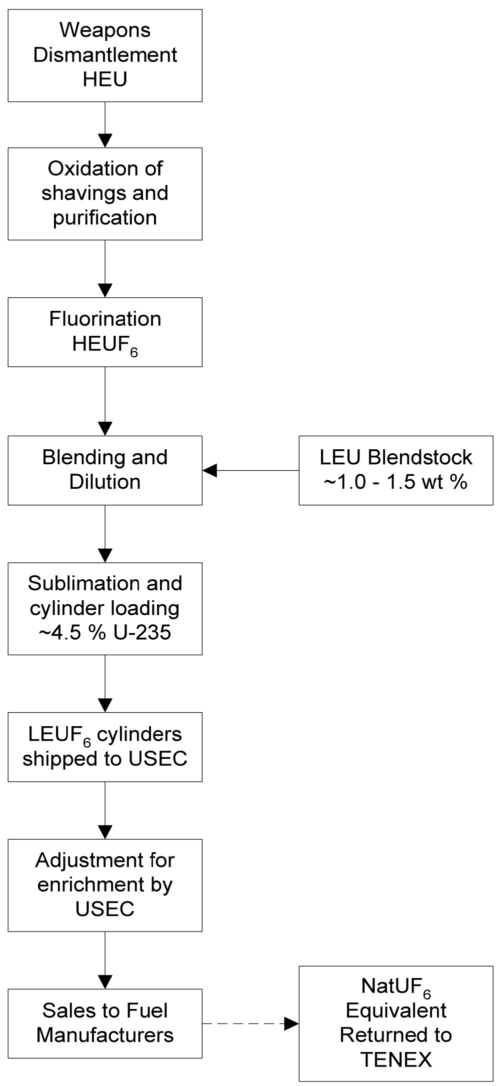


Figure C2-2. Russian HEU to LEU blend process.

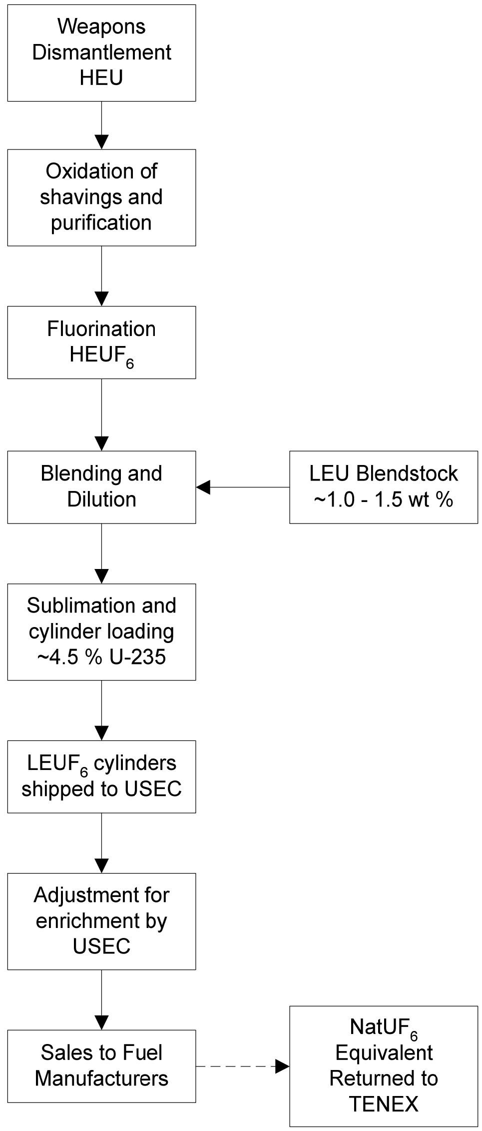


Figure C2-3. Generic U.S. off-specification HEU to LEU blend process. (Selected DOE contractor may modify this generic process.)

## C2-4. MODULE INTERFACES

HEU blending essentially is an alternative to the steps of mining and milling, $U_3O_8$ to $UF_6$ conversion, and uranium enrichment. The $EUF_6$ product is provided directly to the fuel fabricator (basically the same product as from Module C1).

## C2-5. SCALING CONSIDERATIONS

Scaling factors do not apply to this model.

## C2-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

USEC and TENEX are actually paid as they are supplying commercial enrichment and natural feed services. The Russians charge an enrichment price in the low range of commercial enrichment prices. The buyer must provide the natural uranium content and value associated with the LEU. This can be done by a payment or actually providing Russia with $U_3O_8$ or $NatUF_6$. “Flag Swaps” on uranium possession between nations can also be used to avoid transportation costs.

The remainder of this section summarizes historical blend-down activities and addresses prospects for this supply source going forward.

### C2-6.1 Blend-Down Activities to Date (i.e. thru 2012)

In July 2012, USEC announced that it had received the LEU equivalent of 450 tonnes of HEU from Techsnabexport (Tenex), fulfilling another milestone under the Megatons to Megawatts Program (USEC 2012). Megatons to Megawatts implements the US-Russian HEU Purchase Agreement and is on track to reach its final objective of downblending 500 tonnes of HEU by the end of 2013. The 450 tonnes of HEU received as of July 2012 have been fabricated into LEU with a natural uranium equivalent (NUe) of approximately 88,000 tonnes[e] (Khlopkov 2011). At the same time, the United States has downblended 119 tonnes of HEU that had been declared surplus to the nuclear weapons program, although only 93 tonnes (about 18,000 tonnes NUe) has been committed to the civilian power reactor fleet as of 2012 (US DOE EIA 2012). Together these activities have supplied nearly two years’ worth of world uranium requirements at 2012 consumption rates.

### C2-6.2 Blend-Down Activities after 2013

HEU downblending is expected to play a diminishing role in meeting uranium demand, if only because the stocks of HEU that could be made available for future use are smaller than those that have already been downblended (see section C2-1.3).

As reported in the 2009 CBR, the Russians in 2006 indicated they would not extend the Agreement past its 2013 expiration date. A 1992 antidumping law banned Russia from selling LEU in the American market outside the Agreement; the 2009 CBR also described an amendment (the ‘Suspension Agreement Amendment’) to the 1992 law that would allow Russia to market limited amounts of LEU and enrichment services in the US. The quotas specified in the amendment will permit Russia to compete for up to 20 percent of the US market for LEU. In 2010 Tenex opened a US subsidiary, TENAM Corporation, to market Russian uranium and enrichment services; as of mid-2012, TENAM has concluded a number of contracts to supply US power reactors with fuel after 2013 (Khlopkov 2011).

Downblending activities will likely continue in Russia after 2013, though not at the pace of nearly 30 tonnes HEU/year that prevailed during the Purchase Agreement years. A US law passed in 2008 (the ‘Domenici Amendment’) would raise the US market share for which Tenex could compete from 20% to 25% if Russia continued to downblend HEU at 30 tonnes/year and committed to the disposition of an additional 300 tonnes of HEU (Pomper 2008). But as of 2012 the Russian government has not assented to these conditions.

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[e]. *Natural uranium equivalent (NUe)* is defined as the mass of NU obtained if a resource were enriched or downblended to 0.711% U-235. The NUe is difficult to define for HEU since its enrichment level is generally not known. Throughout this section, it will be assumed that the HEU contains 90% U-235 and is downblended with DU assaying 0.25% U-235. Then a mass balance shows that blending 1 kg of HEU with 194 kg of DU yields 195 kg of uranium with enrichment equal to that of NU. So the NU equivalent of HEU is taken to be 195 kg NUe / kg HEU.

Therefore, the World Nuclear Association forecasts that the rate of Russian HEU downblending will decline to less than 20 tonnes/year after 2013 (WNA 2011). This translates to around 3,000 tonnes NUe/year of lost supply – close to 5% of world annual requirements – that must be made good from other sources. Likewise, the smaller US HEU disposition program is decelerating, with only 56 tonnes remaining of the 175 tonnes NNSA had declared its intent to downblend in the near term (US DOE EIA 2012).

## C2-6.3 Remaining HEU Inventories

As of late 2010, the US DOE held 89 tonnes of excess HEU in inventory (US GAO 2011): the 56 tonnes mentioned above plus an additional ca. 34 tonnes subsequently declared surplus by NNSA. Some of this material is allocated: for instance, in 2005 DOE set aside 17.4 tonnes of HEU for the American Assured Fuel Supply (AFS) program. The AFS was inaugurated in 2011 and in 2012 held 230 tonnes LEU equivalent or actually down blended uranium (US DOE NNSA 2008). AFS is meant to serve as a fuel bank to be marketed in the event of a severe supply disruption. Downblending operations in support of the MOX LEU Inventory Backup Project commenced in 2011. This project commits 12.1 tonnes HEU as backup fuel for utilities participating in the DOE weapons Pu disposition program (US DOE EIA 2012). In 2008, when DOE last released its uranium inventory management plan, approximately 67.6 tonnes of HEU remained unallocated[f] to these or other programs (US DOE NE 2008). DOE plans to place LEU downblended from this unallocated inventory on the market, subject to a constraint that the amount sold per year represents not more than 10% of annual domestic demand.

Counting HEU used for the AFS and MOX Backup Project plus unallocated HEU, but discounting uses that would not result in supply to civilian power reactors (e.g. HEU downblend for research reactors or naval propulsion) and excluding downblending activities that have already placed LEU into the civilian fuel cycle, approximately 97 tonnes of US HEU is estimated to be available as a future source of supply.

Much additional HEU remains within the US and Russian weapons programs. Excluding HEU already declared surplus, the International Panel on Fissile Materials (IPFM) estimates that the Russian weapons program retains over 600 tonnes of HEU. The IPFM places the inventory of the US program at ca. 250 tonnes (Pomper 2008).

It is unlikely that all or even most of this material will be released for use in civilian power reactors, and the Russians have not declared a formal post-2013 HEU disposition policy. The Russian government has indicated that up to 300 tonnes of additional HEU may be declared surplus to their weapons program in the future (OECD 2010), but this position cannot be taken as a commitment with a time frame.

HEU inventories in other nuclear weapons states are small and their management policies are not expected to have a substantial effect on the uranium or enrichment markets. Defense-related HEU stocks in China, for instance, have been estimated to lie between 12 and 26 tonnes (Zhang 2011).

In summary, excluding US and Russian HEU already committed to near-term civilian use via the Purchase Agreement and US downblending programs, the following HEU stocks may become available for post-2012 use in civilian power reactors:

- 29.5 tonnes of US HEU via the American AFS and MOX LEU Inventory Backup Projects,
- 67.6 tonnes of unallocated surplus US HEU,

[f]. The amount of HEU DOE considers committed to certain activities is not precisely fixed, so 67.6 tonnes is an approximate figure. For instance, DOE plans to downblend 'up to 23 tonnes' [US DOE EIA 2012] of HEU for use as research reactor fuel.

- up to 300 tonnes of Russian HEU not currently declared surplus.

If all of the above were released for civilian use, they would displace approximately 78,000 tonnes NUe of uranium, slightly more than one year of world annual requirement at 2012 levels.

## C2-7. DATA LIMITATIONS

As mentioned, the importance of HEU as a secondary source of uranium supply is expected to decline after 2013. Other secondary supply reservoirs may play a more important role in the future. For example, the 2008 DOE uranium management plan (US DOE NE 2008) reported inventories of over 46,000 tonnes NUe of surplus high-assay depleted, natural and low enriched uranium. This is a considerably larger potential supply than the unallocated US HEU (67.6 tonnes of HEU, ~13,000 tonnes NUe).

Around the world, Ref. (Schneider 2011) estimates civilian NU/LEU stockpiles held by governments and utilities at ca. 150,000 tonnes NUe as of 2011. It places inventories of 'recyclable uranium' – irradiated LEU both still within used fuel and already separated via reprocessing activities – at ca. 270,000 tonnes NUe. Further, (Schneider 2011) estimates that if 2011 depleted uranium (DU) inventories held around the world were re-enriched with secondary tails taken to 0.14% U-235, some 440,000 tonnes NUe would be yielded.

In practice, most recyclable uranium and DU may never be utilized. Outside of limited experiences in France and Russia, recyclable uranium has not been re-enriched and re-fabricated into reactor fuel. Unless uranium prices rise or abundant inexpensive enrichment capacity is available, most DU will simply be stored or disposed. But at some ten years' supply at current annual NU consumption rates, the size of the potential reservoir embodied by DU and recyclable uranium is substantial.

## C2-8. COST SUMMARIES

There is no What-it-Takes table for this module. LEU made from downblended HEU is a direct substitute for LEU created from mining, converting and enriching natural uranium and competes in that market. In fact, DOE regularly publishes prices it obtains when it sells uranium from its inventory on the spot market (US DOE 2011, Report to Congress).

Modelers are advised to treat the cost of purchasing HEU-derived LEU as being equal to the cost of purchasing the amount of uranium that would be required if HEU were not available (Module A1), converting it to $UF_6$ (Module B), and enriching it to LEU levels (Module C1). The quantities of uranium, conversion and enrichment services required are determined from a fuel cycle specific material balance that must be supplied by the modeler.

## C2-9. SENSITIVITY AND UNCERTAINTY ANALYSES

Figure C2-4 is a conceptual illustration of the effect of sales of blended-down HEU, or any other government-held uranium inventory, on the market. The blue curve shows the price-supply relationship for primary uranium from mines. The dark red curve is the demand curve; some elasticity is afforded by the ability of utilities, over the medium term, to adjust the enrichment of tails, so the curve is not vertical. If no secondary supply sources exist, Point 1 is the market clearing point.

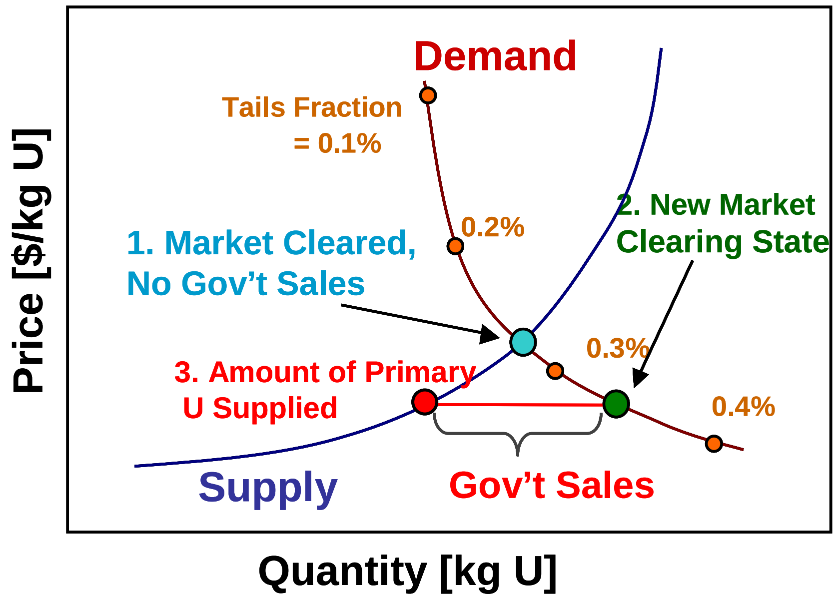


Figure C2-4. Effect of down blended HEU sales on the uranium market.

If government decides to place some uranium on the market, both the price and quantity supplied will change. This secondary uranium may come from government stockpiles as well as HEU blend-down; in fact, the secondary source of uranium could be in private hands, for example utility or producer inventories. Regardless of the source, the secondary uranium has the dual effect of reducing the amount of primary uranium supplied and reducing the market price. In the figure, the quantity of secondary uranium placed on the market is represented by the line connecting Points 2 and 3. The secondary uranium essentially shifts the supply curve to the right by this amount, so that Point 2 becomes the new market clearing state and Point 3 is the amount of uranium supplied by mines. Since the uranium price has decreased, utilities choose to consume less SWU in exchange for more uranium so that the optimal tails enrichment increases.

A situation like the one shown in the figure existed through the 1990s as utilities consumed uranium from stockpiles while down-blended HEU and other varieties of secondary uranium appeared on the market as well. This situation is somewhat analogous to dumping situations that occur from time to time in commodity markets, and its effect of suppressing primary supply over time is well known. Indeed, it is for this reason that DOE has constrained itself to sell only limited quantities of its surplus uranium over the next decade.

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