THE COST STRUCTURE OF INTERNATIONAL URANIUM ENRICHMENT SERVICE SUPPLY

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Abstract

This paper develops an economic model of the international uranium enrichment supply market. With information from planned and operating enrichment facilities, we estimate econometric models of construction cost and labor requirements as exponential functions of facility size. These models are used to estimate Separative Working Unit (SWU) costs of all major enrichers. This allows the tracing of the international SWU supply curve. In a competitive market, the highest cost producer sets the market price. When inefficient gaseous diffusion plants are retired, the SWU price should decline. This could reduce profits for all suppliers and might decrease incentives for future investment in this industry. However, higher prices could encourage potential enrichers to enter the international market. Therefore, to discourage proliferation of enrichment technology, some form of international *market* intervention might be necessary to control SWU prices, in addition to *political* interventions under discussion in the international community to control SWU supply.

Keywords: Gaseous Diffusion, Gas Centrifuge, Separative Work Unit, nuclear power economics

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1. The International Uranium Enrichment Services Market

To increase the percentage of fissile uranium, natural uranium oxide is converted to uranium hexafluoride (UF6, a gas above 56º C), then enriched to a higher percentage of the fissile isotope U^{235}. Enrichment is done commercially using two methods: gaseous diffusion and gas centrifuge. With gaseous diffusion, the UF6 is forced through a series of barriers that allow the smaller U^{235} to penetrate more easily than the larger U^{238}. Given that the difference in weight is small, this process requires pumping UF6 through hundreds of barriers to achieve an enrichment of 3-5% for nuclear reactor fuel. With centrifuge technology, the UF6 is separated through a centrifugation process. Both processes operate in a cascade arrangement where different separation stages are tied together with intricate piping systems. Due to the higher separation factor per stage, a smaller number of centrifuge stages are required to achieve the same level of enrichment than with gaseous diffusion.

Historically, France and the United States dominated the enrichment market with gaseous diffusion. But firms using centrifuge technology, such as the Russian Rosatom and the British-Dutch-German Urenco, have captured an increasing share of the market. The U.S. Enrichment Corporation's (USEC's) share declined from 39% in 1995 to 17% in 2005, as 1940s and 1950s era diffusion facilities (at Oak Ridge, TN, and Portsmith, OH) were retired (Rothwell, 2003).

On the other hand, centrifuge capacity is being built in France and the United States. In France, Eurodif (a member of the Areva group) has partnered with Urenco to produce centrifuges. In the United States, the Department of Energy (U.S. DOE) has helped USEC develop a new generation of centrifuges to replace USEC's diffusion capacity. Testing of the first cascade began in September 2007. Also, Urenco is building centrifuge capacity in New Mexico, and Areva has announced plans to build another centrifuge facility in the United States.

Further, the Brazilian INB (Indústrias Nucleares do Brasil) is building a small enrichment facility at its Resende integrated-nuclear-fuel-cycle site to assure fuel supply of its two nuclear power plants. Argentina, which has two small, de-activated enrichment facilities, is now considering re-activating them. South Africa is interested in refurbishing and expanding its uranium enrichment facility at Pelindaba. Australia is considering building an enrichment facility (possibly using laser enrichment technology) to increase the value added to its uranium resources. With huge diffusion facility retirements and new centrifuge facilities under construction, market capacity and price will be uncertain during the coming transitional decade.

The Appendix forecasts marginal costs for enrichment services, measured in Separative Work Units (SWU). We develop a cost engineering model of four currently planned centrifuge enrichment facilities, and statistically estimate scale parameters from available data. Using long-run levelized cost as a proxy for long-run marginal cost, we calculate marginal costs and construct SWU supply curves for 2005 and 2015.

We show that industry profits could fall with the retirement of the diffusion plants, if prices are determined by competitive markets. This could lead to a lack of investment in the international uranium enrichment industry by profit-making companies in "fuel-cycle" states. If market power is used to sustain higher prices, small new entrants could believe they might be able to compete in the enrichment market. New entry by "non-fuel-cycle" states implies the proliferation of uranium enrichment technology. Because the proliferation externality associated with enrichment is not reflected in the price of enrichment services, free markets do not necessarily lead to socially optimal outcomes. Hence, some form of *market* intervention could be necessary to insure non-proliferating capacity investment and prices near production cost.

2. The Supply Curves of Existing and Future Enrichment Services

We can apply the results of the Appendix to approximate the supply curve for the existing international commercial uranium enrichment services. See Figure 1 for 2005 and Figure 2 for 2015. In Figure 1 we assume that Russian production is limited such that the Novouralsk facility (with 9 M SWU per year) is not competing in the international market (due to agreements associated with blending down weapons grade highly enriched uranium and domestic commitments). See Mikhailov (1995). In Figure 1, about one quarter of the international enrichment market is low cost (less than $50), one quarter is moderate cost (between $50-$100), and one half of the market is high cost (more than $100). With requirements at 40 million SWU (approximately 120,000 SWU per GW per year), the market price is determine by the highest cost producer (USEC) at approximately $135/SWU. (Of course, cheaper producers could under cut Eurodif's and USEC's price in long-term contracts.) With a price of $135/SWU and quantity of 40 M SWU, total industry annual revenues at Fourth-Quarter-2006 prices were about $5,400 M.

With the retirement of the world's diffusion capacity and no constraints on Russian participation in the market, the supply curve for enrichment services will shift between now and 2015 to a situation more similar to that in Figure 2 (which includes Brazilian capacity, in the top right-hand corner). At 2005 quantities (40 M SWU) world requirements could be satisfied by all enrichers, and total revenues would be approximately $3,200 M. If requirements do not grow between 2005 and 2015, then the Japanese (Rokkasho) facility would set the spot market price at least $80/SWU in 2006 dollars: A price drop of 41%, and big savings to consumers of nuclear generated electricity, i.e., $2,200 M.

To understand the implications of these changes, consider economic profits in 2005 versus 2015 (economic profits are net revenues after payments to debt and a reasonable rate of return on equity; accounting profits are net revenues after payments to debt, see Rothwell and Gomez, 2003, p. 25). In Figure 1 the “Russian” box represents Russian economic profits, equal to ($135 ─ $31) (9 M SWU), or about $900 M (not including profits from other facilities and services). In Figure 1 the “Urenco” box represents Urenco’s economic profits, equal to ($135 ─ $70) (8.1 M SWU), or $525 M. In 2015 the profit situation changes: In Figure 2 the “Russian” box represents Russian profits, equal to ($80 ─ $40) (19 M SWU), or about $760 M (taking a weighted average across all facilities) and the “Urenco” box represents Urenco’s economic profits, equal to ($80 ─ $62) (8.1 M SWU), or $145 M.

Therefore, as uneconomic diffusion capacity is retired and all Russian capacity enters the international market, Russian economic profits could decline 16%, but Urenco’s profits could decline by 72%! Because of their more mature technology, Eurodif’s George Besse II and Urenco’s NEF could earn economic profits, but USEC’s APC, might not earn significant economic profits (e.g., $30M per year on an investment of $3,000 M). This situation could make private financing for private enrichers difficult to acquire capital at costs that will allow them to be competitive.

Additional enrichment capacity might be built in Russia, since their centrifuge technology and costs are lower than the comparable Western European centrifuges. One technique of increasing enrichment market share is the creation of an International Uranium Enrichment Center (IUEC) in Angarsk in western Siberia. The Angarsk enrichment and conversion plants have been combined with Kazakhstan’s uranium supplies, since Kazakhstan has joined the IUEC as an equity partner. A fuel pellet plant operating in Kazakhstan might be upgraded to provide fabrication services. In this way the IUEC could provide nuclear fuel at a lower market price, increasing its nuclear fuel market share, and thus its enrichment market share. (The concept of taking equity partners in an enrichment facility to reduce the lead country risk and capital contribution was done to finance the Eurodif facility in France; France might finance the second stage of the George Besse II facility in a similar way.)

3. Conclusions

With the retirement of diffusion technology during the next decade, the artificially high price of enrichment services could fall. (It is “artificially” high due to entry barriers: had a free market developed in enrichment, new cheaper capacity would have forced the retirement of the diffusion technology much earlier). The enrichment industry is now being more closely watched with the discovery of a Pakistani enrichment smuggling network, Braun and Chyba (2004). Thus, entry of new participants into the enrichment market is constrained by nonproliferation considerations, as well as by commercial interests. The enrichment industry response could be the formation of a cartel to maintain artificially high prices. Unfortunately, high prices could encourage entry by countries like Argentina, Australia, Brazil, Iran, South Africa, and others.

Without market intervention, prices could fall to competitive levels. This implies there would be no economic profits in this industry for new entrants. For this reason, the financial outlook of uranium enrichers has been bleak, prompting a Standard and Poor’s analyst to write:

“On 29 September 2006, Standard & Poor’s Ratings Services affirmed its ‘A-/A-2’ long- and short-term corporate credit ratings on Europe-based uranium enrichment company Urenco Ltd . . . The enrichment market is undergoing very drastic changes, as TENEX (Rosatom)—which controls roughly 50% of global enrichment capacity but only 24% market share among end-customers—is looking to increase its share of direct sales to end-customers. The extent to which this will affect Western enrichment suppliers—USEC Inc. (B-/Negative/--), Areva (not rated), and Urenco—over the medium term remains to be seen, but will be strongly influenced by ongoing political and trade negotiations . . . The other major industry change is an expected phase-out of the non-economical gaseous diffusion plants used by USEC and Areva, both of whom are expected to build centrifuge plants in the medium to long term.”

A- implies that Standard & Poor's believes that the "economic situation can affect finance" and "it is likely to be… downgraded (negative);" B- implies a likely downgrade of non-investment grade (junk) bonds where "financial situation varies noticeably," i.e., USEC's must pay junk bond rates on its debt, while trying to finance a new, First-of-a-Kind technology. On the other hand, the U.S. Congress has recently approved $2,000 M in loan guarantees to USEC.

Therefore, assuring adequate enrichment capacity over the long term (e.g., the planning horizon of countries like Brazil) will be problematic without some market intervention. This could take the form of an internationally-recognized uranium enrichment regulator that would guarantee a reasonable rate of return on new enrichment facility investments at a price that would not encourage entry by marginal countries attempting to assure their own country's nuclear power industry enrichment requirements, as claimed by Iran. On the other hand, fuel cycle states could guarantee a profitable price for uranium enrichers, tax the enrichers, and use these taxes to subsidize enrichment services to non-fuel cycle states. Whatever the solution, assuring adequate investment in a centrifuge technology non-proliferation regime will be problematic for any single country to achieve.

Another observation can be made: Any program for assured nuclear fuel supplies to compensate countries willing to give up uncompetitive domestic enrichment facilities should be coupled with lower international enrichment prices to discourage new entrants. The fuel bank proposals should be encouraged, but few of these proposals discuss reasonable prices for the fuel bank services, or whether a fuel bank would be necessary if the SWU price were set artificially low (through subsidies). A subsidized SWU price should be low enough to eliminate any commercial incentive for new enrichment entry. Setting an unreasonably low price might be possible in a regulated or cartel setting, but is unlikely in a "free" market. Because of the externality associated with nuclear weapons technology proliferation, markets in enrichment do not necessarily lead to a social optimum. Subsidies to enrichers to lower enrichment prices to below competitive levels, while increasing capacity, would signal countries considering nuclear power plants that they would never be able to produce fuel at costs below the low-volatility, subsidized price. However, setting an artificially low SWU price would encourage inefficient uranium consumption (i.e., pressure to raise the tails assay); therefore the tails assay must also be set with the price to insure economic efficiency.

Appendix: Cost Models of International Enrichment Facilities

Paul J.C. Harding, the Managing Director of Urenco (Capenhurst) Ltd (UCL), described production at his plant in 2005 (to explain his plant's dependency on non-interruptible power):

"• 40% of Urenco's total current enrichment capacity is at UCL
- UCL has 390 employees
- Annual electricity consumption is 180,000 MWh (~ 20MWe continuous demand)
- Once started, aim is never to stop gas centrifuge machines
    - Need no maintenance
    - Low failure rate
    - Oldest machines at site have run continuously since 1982!
    - If machines are stopped, risk is they will not start again"

To account for the capital, labor, electricity, and other expenses in enrichment services, let total annual cost in 2006 dollars, *TC*, of producing total annual SWU be $p_K K + p_L L + p_E E + p_M M$, where K is the total capital investment cost (TCIC, defined in EMWG 2008) measured in millions, M, of 2006 dollars, and p_K is the annual capital charge rate; L is the number of employees at the facility, and p_L is annual (burdened) salary of an employee; E is the electricity input MWh, and p_E is the price of electricity in dollars per MWh; M represents the cost of materials consumed in the enrichment process, and p_M is the price of materials.

We assume that (1) M is a linear function of K, and (2) p_M is expressed in percent per year of K (this is similar to setting p_M to the physical depreciation rate). Let $p_{KM} = p_K + p_M$. The Levelized Cost, or Long-Run Average Cost, AC, is

$$AC \quad = \quad \Sigma\, (p_{KM} K + p_L L_t + p_E E_t)\,(1 + r)^{-t} \,/\, [\, \Sigma\, SWU_t\,(1 + r)^{-t}\,], \tag{1}$$

where the summation is over the commercial life of the facility, all construction costs are discounted to the commercial operation date and r is the appropriate discount rate. (We implicitly assume, following Harding, 2005, a constant annual capacity factor of 100 percent.)

The remainder of this Appendix proposes and estimates econometric models of overnight costs, k, and labor, L, for new centrifuge capacity. Overnight cost, k, is transformed into total capital investment cost, K, with the addition of Interest During Construction and contingency, i.e., $K = (1 + c) \cdot k$, where c is a percentage mark-up for IDC and contingency. We forecast electricity cost as the product of electricity price and kWh/SWU. With these costs we project long-run marginal cost, and graph supply curves for enrichment services; see Section 2 above.

A.1. Estimating New Centrifuge Enrichment Facility Costs

Overnight construction cost, k, for new centrifuge facilities is estimated with information on four recently announced facilities in the United States, France, and Brazil:

(1) The American Centrifuge Plant (ACP) is being built in Ohio by USEC, using a U.S. DOE-USEC developed 320 SWU/year centrifuge. USEC estimates the first stage will cost \$2,300 M in 2007 dollars (about \$2,230 in 2006 dollars) for a capacity of 3.8 M SWU. The first stages should be producing by 2009 and the facility should be completed by 2012 (USEC, 2007).

(2) The Urenco New Enrichment Facility (NEF) facility in New Mexico with a 3 M SWU per year capacity is based on Urenco technology (TC-12 machines) with a separative capacity of 50 SWU per centrifuge per year. Construction started in August 2006 with the first set of stages

to operate in 2010, and full capacity operation expected in 2013. The overnight cost has been estimated at $1,500 M (in 2006 dollars); see Schnoebelen (2006).

(3) The new George Besse II enrichment facility, with a capacity of 7.5 M SWU per year, near Tricastain, France, is also based on Urenco's TC-12 centrifuges. This facility is being built by Eurodif, a member of the French Areva group. The estimated cost is € 3,000 (2003) M (or $3,275 M 2003 dollars, or $3,700 M 2006 dollars); Autebert (2006).

(4) The Brazilian government is building an enrichment facility at Resende to supply 203,000 SWU by 2015 for its Angra 1 and 2 nuclear power plants. They are using an indigenously developed centrifuge design. The estimated overnight cost is about 550 M 2006 Brazilian Real, or about $253 M 2006 dollars (Cabrera-Palmer and Rothwell, 2008).

Before analyzing this information, we caution that the following cost-engineering -econometric model is based on three centrifuge technologies at different maturities: The Urenco TC-12 centrifuges have been in commercial operation for more than a decade and can be reproduced at N^{th}-of-a-Kind cost. The smaller Brazilian centrifuges are in their First-of-a-Kind commercial deployment. The ACP larger centrifuges are being scaled up from prototype to commercial size. Therefore, these are conditional estimates and should be revised when more cost information is publicly available.

With this information we estimate an exponential model of *k* (overnight cost in millions of 2006 dollars) as a function of annual SWU capacity (*SWU* in thousands of SWU per year), i.e., the Ordinary Least Squares (OLS) parameter estimates are

$$\ln(k_i) = \underset{(0.38)}{1.62} + \underset{(0.05)}{0.73} \ln(SWU_i) \qquad (R^2 = 0.99, F = 228.54), \tag{2}$$

where values in parentheses are standard errors. All indications are that this equation is well estimated, see graph in Figure A.1. From these results, we conclude there are increasing returns to scale in capital (with a scale factor of 0.73 and a standard error of 0.05, there is 99 percent confidence that the scale factor is not equal to 1.0, as it would be under constant returns to scale).

In industries where there are increasing returns to scale, the largest producer can undercut the price of smaller producers. This can lead to the creation of market power and to prices higher than costs. On the other hand, in the enrichment industry, increasing returns to scale provides a barrier to entry, thus increasing the proliferation resistance of the industry, and therefore reducing the social cost of the proliferation externality. Increasing returns to scale in enrichment reduces both proliferation and market price discipline. Hence, there is a tension between profits (under high prices, which encourage proliferation) and non-proliferation (under low prices).

The difference between overnight costs (k) and total capital investment costs (K) is the addition of Interest During Construction (IDC) and contingency. IDC discounts construction expenditures to the start of commercial operation. It is a function of the cost of capital and the construction length. Because centrifuge enrichment facilities can be built in modules, IDC is charged over the lead time of module construction. We assume this lead time is 3 years. At a cost of capital of 5 percent, IDC adds 7.48 percent to the cost of the project. Following EMWG (2008), we assume a contingency of 10%. So $K = (1 + 0.0748 + 0.10)\ k = 1.1748\ k$.

The price of capital, p_K, is the annual capital charge rate. Following Cabrera-Palmer and Rothwell (2008), we assume a 5 percent *real* cost of capital with centrifuge economic plant lives of 30 years, i.e., $p_K = 0.0651$. (The real cost of capital is equal to the nominal cost of capital minus the expected inflation rate; with expected inflation at 3 percent, the nominal cost of capital would be 8 percent, i.e., one appropriate for a regulated utility.) Also, we assume that the annual physical depreciation cost is 1 percent of overnight costs, i.e., $p_M\ M = 0.01\ k = 0.01/1.1748\ K = 0.0085\ K$). So, $p_{KM} = 6.51\% + 0.85\% = 7.4\%$. (Although EMWG, 2008, recommends financing plant decommissioning through a sinking fund, because the throughput of these facilities is so high, the decommissioning cost per SWU is low enough to be ignored at this level of analysis.)

Second, regarding labor, *L*, the announced projected staff size of the ACP is 500 employees (USEC 2004), the staff size of NEF has been announced to be 210, and the staff size of Resende is estimated to be 100 (Cabrera-Palmer and Rothwell 2008). Also, while not a new facility, there are 390 employees at Urenco's Capenhurst facility (producing 3.4 M SWU per year). This provides a benchmark and another observation. With this information we estimate an exponential model of *L* (staff size) as a function of size (*SWU* in thousands of SWU per year). The OLS parameter estimates are

$$\ln(L_i) = \underset{(1.22)}{2.16} + \underset{(0.16)}{0.46}\ln(SWU_i) \qquad (R^2 = 0.80,\ F = 7.91), \tag{3}$$

where values in parentheses are standard errors. This equation is not as well estimated as Equation 2, see graph in Figure A.2. However, the equation does well at forecasting the staff size at Capenhurst. We conclude there are increasing returns to scale in labor. (With the scale factor equal to 0.46, and a standard error of 0.16, there is 98 percent confidence in rejecting constant returns).

Further, we assume a "fully burdened" average annual salary is $60,000 in Brazil, based on a base salary of approximately $35,000 per year (Cabrera-Palmer and Rothwell, 2008) and a 70 percent burden rate (EMWG 2008). Also, we assume a burdened average annual salary in France and the United States is $120,000, based on information in the annual reports of the ETC

(Enrichment Technology Corporation, a joint venture between Urenco and Areva to produce centrifuge equipment): The 959 employees at ETC in 2006 were paid €65.943 M, or €69,000/employee/year (ETC, 2007), which is approximately twice the salary paid in Brazil.

Third, the electricity consumption for Urenco and ACP centrifuges is from INL (2007), i.e., 50 kWh/SWU. The electricity consumption for Resende centrifuges is from Cabrera-Palmer and Rothwell (2008), i.e., 100 kWh/SWU. Further, following Cabrera-Palmer and Rothwell (2008), we assume $92/MWh (or $0.092/kWh) as the delivered price of electricity (in 2006 dollars) for all centrifuge facilities, which includes transmission and distribution fees (generally, generation is one-half of total costs, i.e., the generation cost is approximately $46/MWh).

Table I presents the estimated levelized cost per SWU for the new centrifuge facilities assuming a real 5 percent cost of capital. The capital intensity of centrifuge enrichment technology yields an annual capital charge that is 2/3rds of the total annual cost. Labor is about 1/6th of total costs, and electricity and materials make up the remaining 1/6th. The Urenco technology facilities (NEF in New Mexico and George Besse II in France) will likely have lower costs than the USEC's ACP. The levelized cost of Brazil's small facility will likely be twice as much as cost at the ACP, and almost three times as much as cost at the Urenco facilities. Next, we apply this economic model to estimate costs of the existing enrichment facilities.

A.2. Projecting Replacement Costs of Existing Centrifuge Facilities

Next, we approximate the cost structure of the existing commercial centrifuge facilities owned by Urenco, JNFL, and Rosatom. See Tables II and III. Urenco has three production facilities at Capenhurst, the UK, with 3.4 M SWU; Almelo, the Netherlands, with 2.9 M SWU; and Gronau, Germany, with 1.8 M SWU. Using Equation (2), we estimate the overnight replacement cost (in 2006 dollars). Because these facilities have already been built and some of the capital has been depreciated, we assume that there is no contingency or IDC, i.e., that total capital investment cost (*K*) is equal to the estimated overnight replacement cost (*k*). (This assumption reduces the levelized capital costs at older facilities by 10 percent.) We assume that Urenco and JNFL determine their annual capital charge using a real 5 percent cost of capital. The Urenco facilities yield levelized costs in the same range as the new facilities in the United States. Costs at Rokkasho, Japan, are higher due to the lack of scale economies in capital and labor (also Japanese levelized costs could be much higher given lower capacity factors at Rokkasho.)

The same analysis is applied to estimate the costs at Rosatom's centrifuge-based facilities in Novouralsk (UEKhK, Sverdlovsk Oblast) with 9 M SWU, Zelenogorsk (EKhZ, Krasnoyarsk Kray) with 5 M SWU, Seversk (SKhK, Tomsk Oblast) with 3 M SWU, and Angarsk (Irkutsk Oblast) with 2 M SWU. (See Bukharin 2004.) Again, we assume the replacement values of the facilities can be modeled with Equation (2) and labor requirements with Equation (3). In determining appropriate parameter values, we follow Bukharin (2004, p. 199): "large separative capacities and low production cost – possibly on the order of $20 per SWU (compared to approximately $70 per SWU in the United States) – which is made possible by the use of highly-efficient centrifuge technology, and access to low-cost electricity, materials and labor, make the Russian enrichment enterprise highly competitive." Therefore, we assume (1) that the real cost of capital is 2.5%, leading to a capital recovery factor of 4.78% (versus 6.51% for the other centrifuge facilities), (2) the burdened cost of labor is $60,000 equal to that in Brazil, and (3) a cost of electricity of $46/MWh (implicitly assuming that the cost of transmission and distribution is zero). See Table III. The estimated levelized cost in 2006 dollars is between $31 for the largest facility and $48 for the smallest facility, lower than at all other international facilities. It is possible that costs are even lower, as assumed in Bukharin (2004).

A.3. Projecting Costs of Existing Diffusion Facilities

Finally, we apply our economic model to approximate the cost structure of the existing commercial diffusion plants owned by USEC and Eurodif. See Table IV. Of course, this is a different technology (however, nearly 85% of the cost of diffusion enrichment is determined by the cost of electricity, so all other costs, which we are approximating with our model of centrifuge technology, are of second order). Using the same technique for projecting investment costs as above, we find that the current investment costs (*replacement value*) for each diffusion plant is about $4,000 M. We assume a 2.5% cost of capital to determine the annual capital charge. We assume that Eurodif's newer diffusion plant (completed in 1982) operates at 2,200 kWh/SWU, whereas the older USEC plant (Paducah, completed in 1954) operates at 2,500 kWh/SWU. Because of the size of these facilities, we assume dedicated electricity generators at $46/MWh (i.e., again, implicitly, the transmission and distribution costs are zero). This high use of electricity makes the gaseous diffusion plants the highest cost producers in the international enrichment industry (with almost half the world's capacity). These two plants are due to retire by 2015. We use these results to trace supply curves in Section 2 to determine how the retirement of gaseous diffusion capacity could influence prices in this market.

A.4. Estimating the long-Run Average Costs of Centrifuge Facilities

Given the high cost of the small plant and the similarity of costs for the large plants (indicating the possibility of declining scale economies), we use a reciprocal functional form to model the relationship between average cost (AC) and size (SWU): $AC = \gamma + \delta (1 / SWU)$. Average cost is calculated for various plant sizes at costs of capital of 5% and 10%. These calculated costs are compared to the inverse of plant size. This relationships presented in Figure A.3. (Here, economies of scale are nearly exhausted at 2.5 million SWU.) So, if a plant had a capacity of 1 million SWU per year with r = 10%, the levelized average cost would be approximately \$69.59 + \$18.93 = \$88.52/SWU. This information is used to graph the supply curves in Section 2.

FIGURES

Figure 1. Supply of Uranium Enrichment Services, 2005

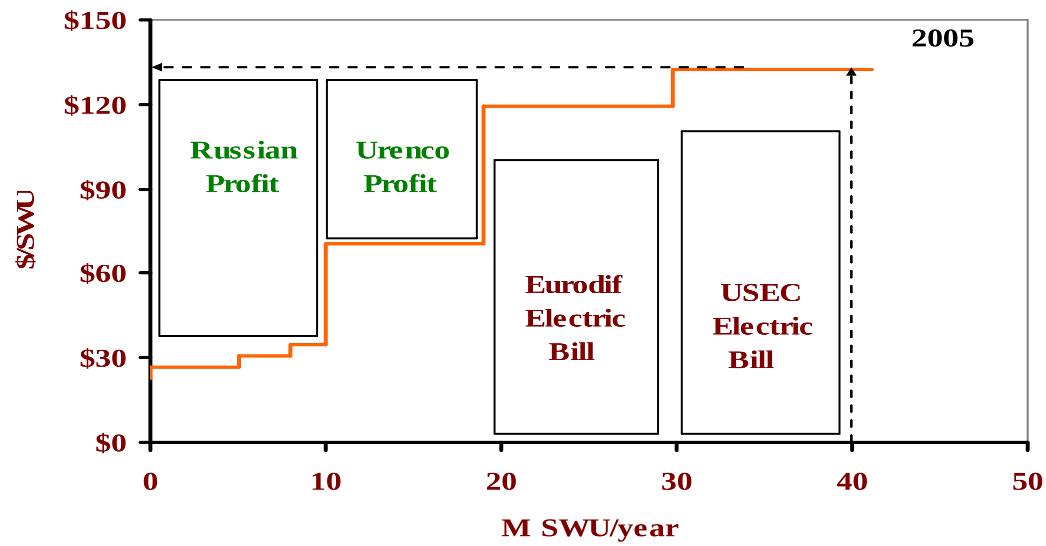


Figure 2. Supply of Uranium Enrichment Services, 2015

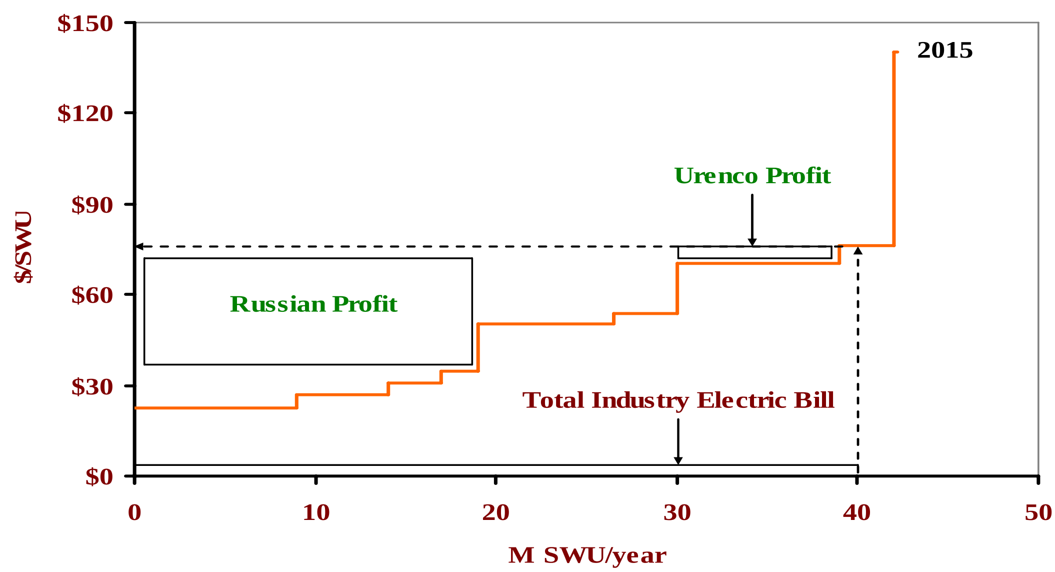


Figure A.1. Estimated Overnight Cost, Centrifuge Technology (2006 dollars)

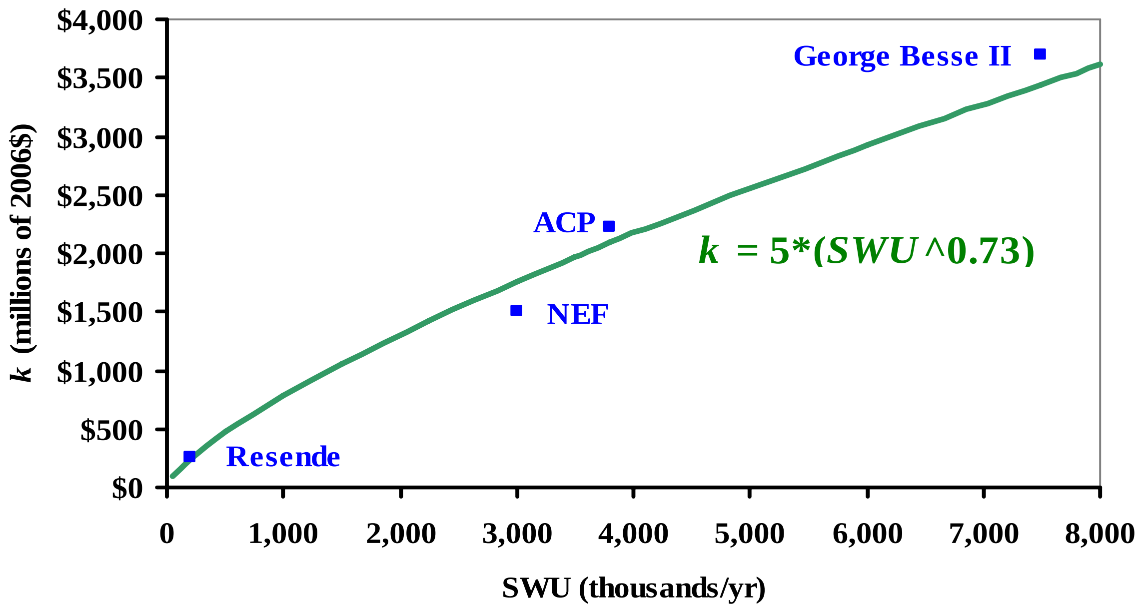


Figure A.2. Estimated Labor, Centrifuge Technology

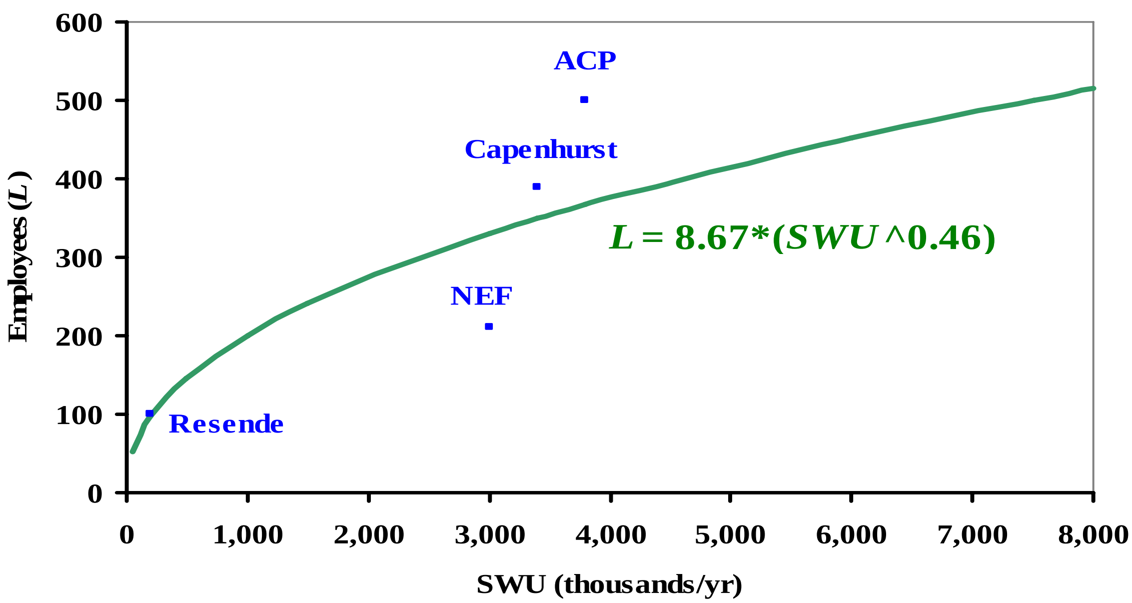
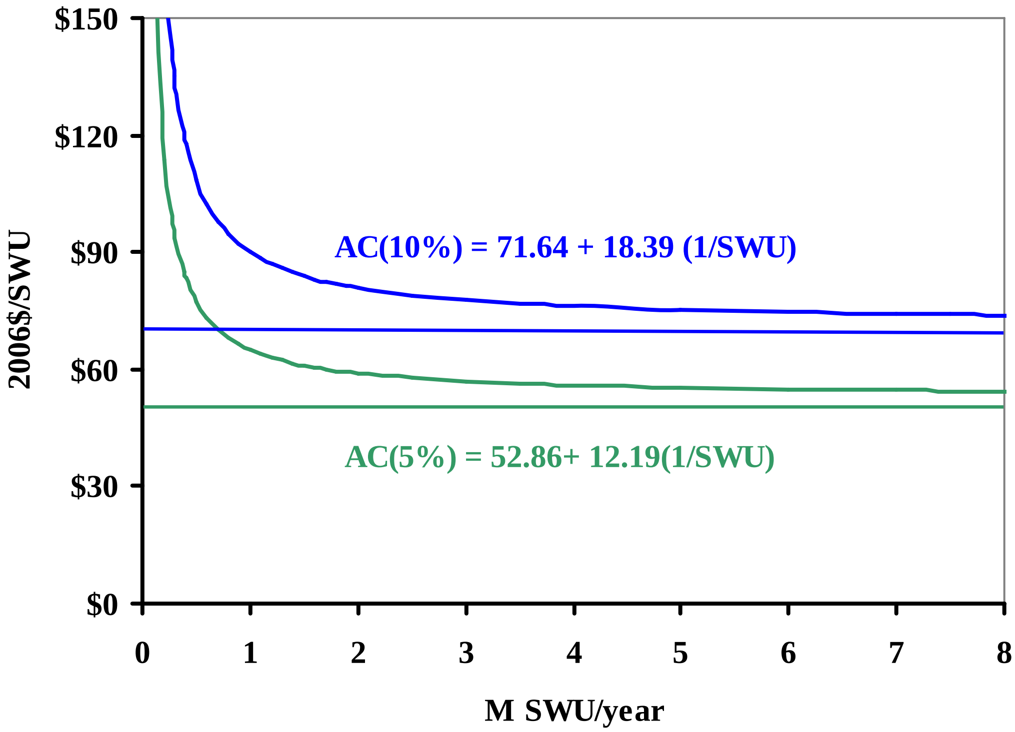


Figure A.3. Estimated Cost Curves, Centrifuge Technology



TABLES

Table I. Levelized SWU Costs, New Centrifuge Capacity
(5% cost of capital, 6.51% Capital Recovery Factor, +7.48% IDC, 10% Contingency)

Firm **Facility**	(2006 $)	**USEC** **ACP**	**Urenco** **NEF**	**Eurodif** **Besse II**	**INBrazil** **Resende**
Plant Capacity	k SWU/yr	**3,800**	**3,000**	**7,500**	**203**
Overnight Cost (*k*)	$M	**$2,230**	**$1,500**	**$3,700**	**$253**
Total Capital Invest Cost (*K*)	$M	**$2,645**	**$1,779**	**$4,389**	**$300**
Annual Capital Charge	$M	**$172**	**$116**	**$286**	**$20**
Staff Size (L)	people	500	210	525	100
Annual Fully Burden Salary	$k/yr	$120	$120	$120	$60
Annual Labor Cost	$M	**$60**	**$25**	**$63**	**$6**
Electricity Consumption	kWh/SWU	50	50	50	100
Electricity Price	$/MWh	$92	$92	$92	$92
Annual Electricity Cost	$M	**$17**	**$14**	**$35**	**$2**
Annual Materials Cost	$M	**$22**	**$15**	**$37**	**$3**
Annual Total Costs	$M	**$272**	**$170**	**$420**	**$30**
Levelized SWU Cost (*AC*)	$/SWU	**$72**	**$57**	**$56**	**$147**

Table II. Levelized SWU Costs, Existing Centrifuge Capacity (Europe and Japan)
(5% cost of capital, 6.51% Capital Recovery Factor, +0% IDC, 0% Contingency)

Firm **Facility**	(2006 $)	**Urenco** **Capen-hurst**	**Urenco** **Almelo**	**Urenco** **Gronau**	**JNFL** **Rokkasho**
Plant Capacity (in millions)	k SWU/yr	**3,400**	**2,900**	**1,800**	**1,250**
Overnight Cost (*k*)	$M	**$1,892**	**$1,685**	**$1,189**	**$911**
Total Capital Invest Cost (*K*)	$M	**$1,892**	**$1,685**	**$1,189**	**$911**
Annual Capital Charge	$M	**$123**	**$110**	**$77**	**$59**
Staff Size (L)	people	**365**	**339**	**273**	**230**
Annual Fully Burden Salary	$k/yr	$120	$120	$120	$120
Annual Labor Cost	$M	**$44**	**$41**	**$33**	**$28**
Electricity Consumption	kWh/SWU	50	50	50	50
Electricity Price	$/MWh	$92	$92	$92	$92
Annual Electricity Cost	$M	**$16**	**$13**	**$8**	**$6**
Annual Materials Cost	$M	**$19**	**$17**	**$12**	**$9**
Annual Total Costs	$M	**$201**	**$181**	**$130**	**$102**
Levelized SWU Cost (*AC*)	$/SWU	**$59**	**$62**	**$72**	**$81**

Table III. Levelized SWU Costs, Existing Centrifuge Capacity (Russia)
(2.5% cost of capital, 4.78% Capital Recovery Factor, +0% IDC, 0% Contingency)

Firm **Facility**	(2006 $)	**Rosatom** **Novouralsk**	**Rosatom** **Zelenogorsk**	**Rosatom** **Seversk**	**Rosatom** **Angarsk**
Plant Capacity (in millions)	k SWU/yr	**9,000**	**5,000**	**3,000**	**2,000**
Overnight Cost (*k*)	$M	**$3,851**	**$2,507**	**$1,727**	**$1,284**
Total Capital Invest Cost (*K*)	$M	**$3,851**	**$2,507**	**$1,727**	**$1,284**
Annual Capital Charge	$M	**$184**	**$120**	**$83**	**$61**
Staff Size (L)	people	**571**	**436**	**345**	**286**
Annual Fully Burden Salary	$k/yr	$60	$60	$60	$60
Annual Labor Cost	$M	**$34**	**$26**	**$21**	**$17**
Electricity Consumption	kWh/SWU	50	50	50	50
Electricity Price	$/MWh	$46	$46	$46	$46
Annual Electricity Cost	$M	**$21**	**$12**	**$7**	**$5**
Annual Materials Cost	$M	**$39**	**$25**	**$17**	**$13**
Annual Total Costs	$M	**$277**	**$183**	**$127**	**$96**
Levelized SWU Cost (*AC*)	$/SWU	**$31**	**$37**	**$42**	**$48**

Table IV. Levelized SWU Costs, Existing Diffusion Capacity (U.S. and France)
(2.5% cost of capital, 4.78% Capital Recovery Factor, +0% IDC, 0% Contingency)

Firm **Facility**	(2006 $)	**USEC** **Paducah**	**Areva** **Eurodif**
Plant Capacity (in millions)	k SWU/yr	8,000	11,300
Overnight Cost (*k*)	$M	**$3,534**	**$4,547**
Total Capital Invest Cost (*K*)	$M	**$3,534**	**$4,547**
Staff Size (L)	people	**541**	**635**
Annual Fully Burden Salary	$k/yr	$120	$120
Annual Labor Cost	$M	**$65**	**$76**
Electricity Consumption	kWh/SWU	2,500	2,200
Electricity Price	$/MWh	$46	$46
Annual Electricity Cost	$M	**$1,300**	**$1,093**
Annual Materials Cost	$M	**$35**	**$45**
Annual Total Costs	$M	**$1,569**	**$1,432**
Levelized SWU Cost (*AC*)	$/SWU	**$137**	**$130**

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