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Market Power in Uranium Enrichment

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Abstract

Four firms dominate the international uranium enrichment market. Two reasons for this industrial concentration are (1) enrichment capacity can be used to make nuclear weapons, and hence its spread has been controlled through many mechanisms, including technology classification, and (2) increasing returns to scale, also known as, positive economies of scale. Historically, strong increasing returns to scale in gaseous diffusion technology development and commercialization prevented non-nuclear weapons states from considering uranium enrichment. Later, gas centrifuge technology allowed new entrants to build commercially competitive enrichment plants at much smaller sizes than diffusion technology and at a fraction of the electricity cost. At the same time, the nations that privatized or host privately-owned enrichment facilities have strongly discouraged others from developing enrichment capacity. Therefore, these firms have been benefiting from the exercise of national power to prevent entry into this market. Had there been no control on enrichment capacity, the uncompetitive diffusion capacity could have been retired and the market price could have been lower. Further, non-proliferation is not these firms' primary mission. In situations like this (with increasing returns to scale and difficult to evaluate externalities), firms are usually regulated or nationalized, because free markets do not necessarily lead to the socially optimal level of concentration and diversity in supply, i.e., a long-run equilibrium where the industry is *necessarily concentrated* such that there is no proliferating entry, but is *sufficiently diverse* so that no one national group can dictate prices, contract terms, or non-proliferation policy.

Keywords: gaseous diffusion, gas centrifuge, Separative Work Unit, nuclear power economics

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1. The International Uranium Enrichment Market

In the debate of how to assure nuclear fuel (such that nations considering the building of nuclear power plants do not also consider building uranium enrichment plants), there is little discussion of whether free (unregulated) markets can provide assurances that enrichment capacity will be available to all customers at reasonable prices. There are at least four markets in the front-end of the nuclear fuel cycle that must be reviewed to determine assurance of supply: (1) uranium mining and milling, (2) uranium conversion, (3) uranium enrichment, and (4) nuclear fuel fabrication. Rothwell (2009) finds that the nuclear fuel fabrication of low-enriched uranium into light-water reactor fuel rods is a competitive industry with barriers to entry to discourage investment in fuel fabrication by nations with small nuclear industries. Future papers will examine competition in uranium mining and milling (updating Rothwell 1980) and uranium conversion. This paper examines whether market forces in the uranium enrichment market can lead both to economic efficiency and to socially optimal levels of assured alternative sources of supply, given the risk of enrichment technology spread.

Four firms dominate the international uranium enrichment market: United States Enrichment Corporation (USEC, which was privatized in the mid-1990s), TENEX/Rosatom (Russia), Eurodif/Areva (France), and Urenco (with plants in Germany, the Netherlands, and the United Kingdom). The United States (through the Atomic Energy Commission) monopolized the Western enrichment market with gaseous diffusion and Russia monopolized the Eastern market. The U.S. commercial dominance of gaseous diffusion ended with the entry of Eurodif, a consortium of countries with France as the diffusion technology provider and only producer. However since the 1980s, firms using gas centrifuge technology, including those in Russia and the British-Dutch-German Urenco, have captured an increasing share of the market. USEC’s share of enrichment capacity declined from 39% in 1995 to 14% in 2008, as earlier diffusion facilities (at Oak Ridge, TN, and Portsmith, OH) were retired.

Table I shows changes in capacity shares over the last decade. (Not all of this capacity directly serves the fuel market, as discussed in Section 2; for example, Russia is using excess capacity to slightly enrich uranium to mix with down-blended, weapons-grade, highly-enriched uranium.) The Herfindahl-Hirschman Index (HHI) measures the degree of concentration in an industry.[1] HHI ranges from 100 with an industry of 100 equal-sized firms, to 5,000 in an industry with a duopoly, to 10,000 for a monopoly. The U.S. Department of Justice has considered industries with HHIs above 1,800 to the "highly concentrated," and would have discouraged a merger in these industries if the HHI were to increase by more than 100 points.

Although highly concentrated, from 1995 to 2008, the HHI changed little in this industry as USEC facilities were retired and Russian capacity increased. In the last column of Table I, the HHI is calculated under the assumption that Areva and Urenco ("Euro") do not compete (because they are now using the same centrifuge manufacturer, ETC), the HHI would increase by 600 points, i.e., the industry would become even more concentrated as measured by this metric.

Table I. International Uranium Enrichment Capacity Shares, 1995-2008

Country	Owner	Share 1995	Share 2001	Share 2005	Share 2008	"Euro" 2008
HHI		2,900	2,800	2,900	3,000	3,600
US	USEC	39%	23%	16%	14%	14%
Russia	Tenex	29%	41%	45%	47%	47%
France	Areva	22%	22%	22%	20%	35%
European	Urenco	7%	11%	14%	15%	
Japan	JNFL	2%	2%	2%	2%	2%
China	CNNC	1%	2%	2%	1%	1%

During the next decade, older diffusion capacity will be replaced by newer centrifuge capacity in France and the United States.[2] In France, Eurodif (a member of the Areva group) has partnered with Urenco to produce centrifuges through the Enrichment Technology Company (ETC). In the United States, the Department of Energy (U.S. DOE) has partnered with USEC to develop a new generation centrifuge 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 is building centrifuge capacity in Idaho Falls, Idaho.

Further, the Brazilian INB (Indústrias Nucleares do Brasil) is building a small enrichment facility at its Resende integrated-nuclear-fuel-cycle site to assure the fuel supply of its two nuclear power plants (Cabrera-Palmer and Rothwell 2008). 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. An Australian firm, Silex, has licensed its technology to GLE (a partnership of General Electric/Hitachi and Canadian Cameco) http://www.gepower.com/about/press/en/2008_press/062008.htm to build a prototype laser enrichment facility in North Carolina. With diffusion facility retirements and new centrifuge facilities coming online, market capacity, price level, and price volatility will be uncertain during the coming decade. Can we be assured that a international free market in uranium enrichment will lead to socially-optimal levels of enrichment capacity over the foreseeable future?

Neo-classical economic theory shows that society is better off when market prices equal the cost of production, including a reasonable (risk-adjusted) return on capital. When prices do not reflect the costs of production or consumption, economists conclude that the market has "failed," i.e., it has failed to achieve the socially-optimal level of output or investment.

Markets fail for at least four reasons: (1) in industries where there are strong increasing returns to scale (also known as positive scale economies), the largest firms can increase market share to monopoly or near monopoly levels, then raise prices, for example, in software, particularly in operating systems; (2) where unpriced inputs or outputs, known as externalities, influence another producer or consumer's profits or well-being, for example, greenhouse gas production, which is not priced; (3) where consumers cannot be excluded from consumption, for example, from national and local security; and (4) where there is systematic asymmetric information between the buyer and seller, for example in markets where buyers cannot know the riskiness of the seller's financial instruments. See Pindyck and Rubinfeld (2009, p. 315+).

While there might be more than one source of market failure in the international uranium enrichment market (for example, the unpriced proliferation externality associated with enrichment technology), I will focus on the issue of increasing returns to scale. With increasing returns to scale, (1) small producers (such as new entrants) have little economic incentive to enter to compete with established and growing larger producers, and (2) larger producers can eventually drive smaller rivals from the market. This leads to market power where prices can be higher than costs, or where other concessions can be extracted, e.g., the assumption of price risk by the customer, or market power can be leveraged into other markets, such as nuclear reactors.

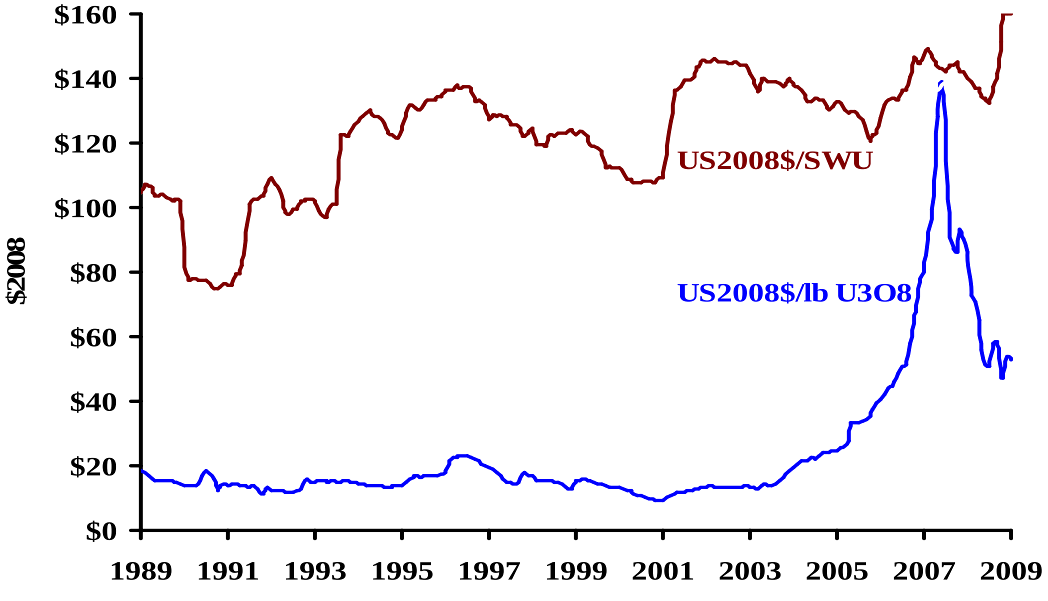
However in the enrichment industry, increasing returns provides a barrier to entry, thus increasing the proliferation resistance of the industry, and reducing the social cost of the proliferation externality. But increasing returns in enrichment reduces both market price discipline and proliferation. Given increasing returns, the economic issue is whether free markets in uranium enrichment can assure optimal long run levels of investment *and* non-proliferation.

Most observers of the enrichment industry assume there are increasing returns to scale.[3] The Appendix tests this assumption and proposes a top-down, microeconomic-engineering model of the industry. Section 2 uses this model to show that if enrichment prices were determined by competitive markets, prices should fall with the retirement of the diffusion capacity. If prices remain high, or if a monopoly develops, or if enrichment technology continues to proliferate from privately-owned enrichers, free markets are not leading to socially optimal outcomes. Hence, Section 3 argues that some form of international market intervention (beyond the patchwork of national subsidies) could be necessary to insure an optimal diversity of non-proliferating capacity investment and prices near production cost.[4] Given the small size of economic profits in this industry and the consequences of proliferation, there is little to be lost in terms of economic efficiency if enrichment price regulation eases the creation of non-proliferation agreements with nations considering entry into uranium enrichment.

2. The Emerging Duopoly in the International Uranium Enrichment Market

To increase the percentage of fissile uranium, U^{235}, from approximately 0.7%, natural uranium oxide ("yellowcake") is enriched to a higher percentage, e.g., 4%. Enrichment is done commercially using two methods: gaseous diffusion and gas centrifuge. During the last 20 years, the real spot price of uranium enrichment, measured in Separative Work Units (SWU) has doubled from $80 to $160 in 2008 dollars. (SWU are measured in kilograms, kgU, or Metric Tons of Uranium, MTU.) See Figure 1.[5] As discussed in the Appendix, the cost of gaseous diffusion enrichment is driven by the price of electricity. As the price of electricity has risen, the cost of diffusion enrichment has risen above the cost of centrifuge enrichment, making gaseous diffusion plants the marginal producers, i.e., those that supply the last segment of demand. As the marginal producers, diffusion enrichers' costs (in association with market demand) appear to determine the spot market price.

Figure 1. Spot Prices for SWU and Uranium, 1989-2009



To represent this market, the Appendix estimates average SWU cost in 2008 dollars for uranium enrichment.[6] The Appendix presents a microeconomic-engineering model of the currently planned centrifuge enrichment plants, and statistically estimates scale parameters.

Using long-run levelized cost as a proxy for long-run marginal cost, levelized costs are used to construct SWU supply curves for 2008 (Figure 2) and 2020 (Figure 3).[7]

In Figure 2 it is assumed that Russian production is limited such that the Novouralsk facility (with 12.45M 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 2, about one quarter of the international enrichment market (Russian) is low cost (less than $60), one quarter (Urenco) is moderate cost (between $60-$100), and one half of the market (gaseous diffusion) is high cost (more than $100). With requirements around 40M (million) SWU (approximately 120,000 SWU per GW per year for 333 GW worldwide), the market price is determined where demand is satisfied by the highest cost producers (those with gaseous diffusion technology) at approximately $160/SWU. (Of course, cheaper producers could under cut Eurodif's and USEC's price with proprietary long-term contracts; so contract prices are not necessarily equal to spot market prices, and revenues and economic profits could be much lower than suggested here.)

With the retirement of the world's diffusion capacity and no international constraints on Russian participation in the market, the supply curve for enrichment services could shift by 2020 to a situation more like that in Figure 3.[8] Assuming growth of 12.5 percent to 45M SWU, world requirements could be satisfied by all enrichers, and maximum total revenues would be approximately $4,500M (in 2008 dollars).[9]

However, as today, USEC could be the marginal producer, so a competitive market should equilibrate to cover USEC's new levelized production costs (e.g., $100/SWU in 2008 dollars). This suggests a price drop of almost 40 percent, and a savings to consumers. However, the industrial concentration, as measured by the HHI, would jump to 3,500 if Areva and Urenco are competing, or to 4,200 if Areva and Urenco are not competing, i.e., the industry would be approaching the concentration of a duopoly (HHI = 5,000) with the Russians and Europeans dominating the international uranium enrichment market. (This analysis does not include Urenco capacity increases from replacing the TC-12 centrifuge with the TC-21 centrifuge; Upson, 2001.)

Figure 2. Supply of Uranium Enrichment Services, 2008

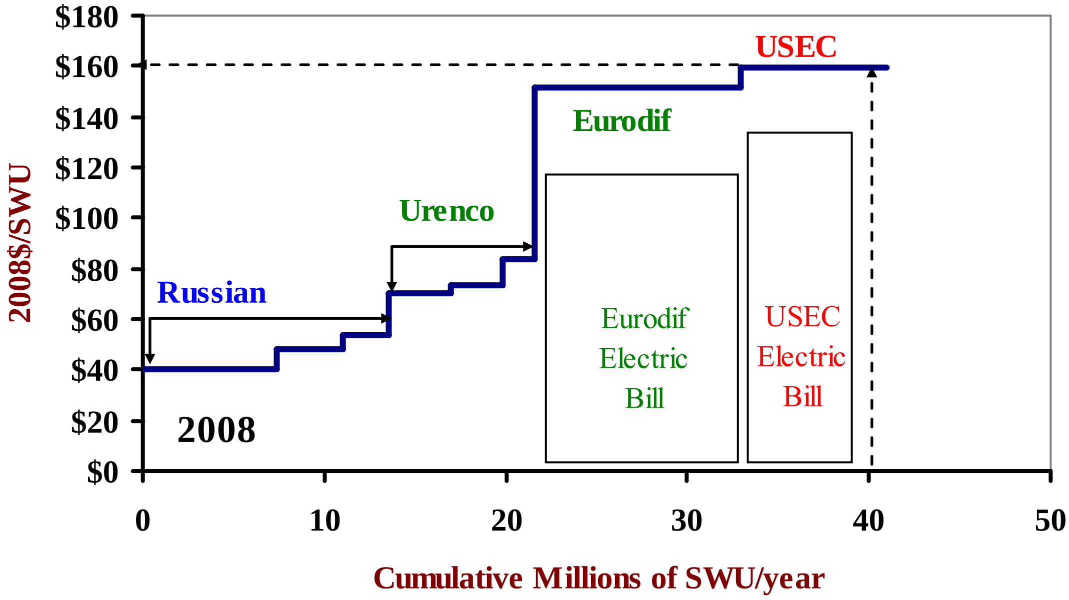
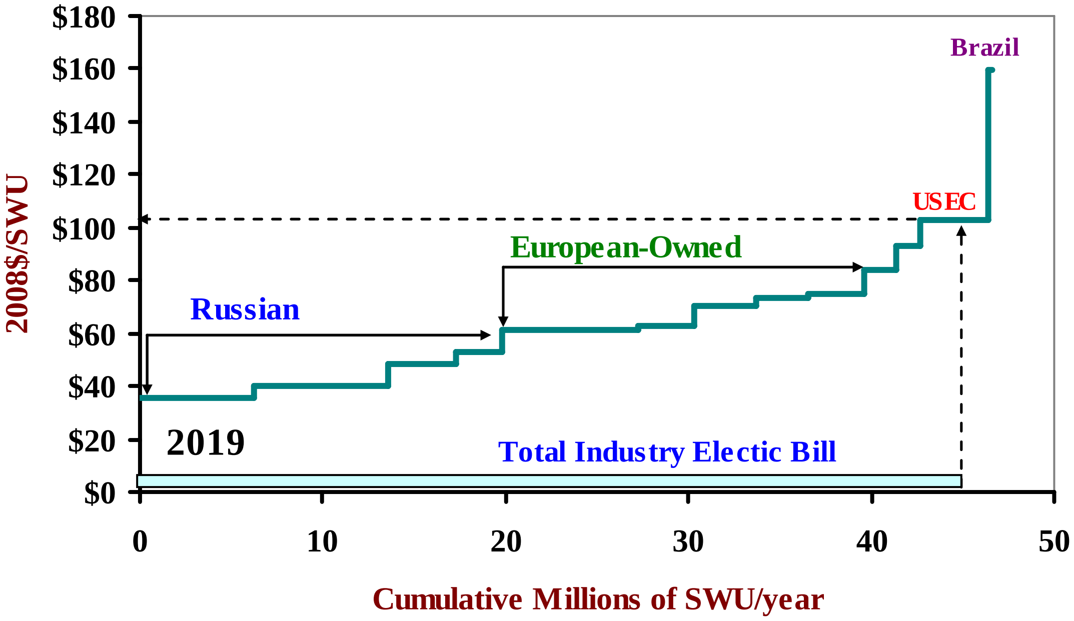


Figure 3. Supply of Uranium Enrichment Services, 2020



Therefore, as diffusion capacity is retired and prices fall to reflect a decline in costs (following competitive market forces), because of their more mature technology, Russia and the Europeans could earn economic profits, but Japan's Rokkasho and USEC's ACP might not earn anything above their reasonable capital and production costs. Anticipation of this situation could make financing for USEC difficult to acquire at a cost of capital that will allow them to be competitive, particularly if credit is tight and their credit rating continues to decline (the U.S. DOE is providing $2,000M in loan guarantees to USEC, see Kinney 2008). The financial crisis could slow ACP completion, thus postponing the retirement of USEC's diffusion capacity, and supporting a higher market price.

Russia is building additional enrichment capacity. One method for increasing enrichment market share is the creation of the International Uranium Enrichment Center (IUEC) in Angarsk, Siberia (see Braun 2006). The Angarsk enrichment and conversion plants have been combined with Kazakhstan's uranium mines. A Kazakhstan fuel pellet plant could be upgraded to provide nuclear fuel fabrication services. If the IUEC could provide nuclear fuel at a lower market price, it could increase its nuclear fuel market share, and thus Russia's enrichment market share.

3. Implications of Enrichment Duopoly Emergence to USEC and the United States

With the retirement of diffusion capacity during the next decade, the artificially high price of enrichment could fall. (It is "artificially" high due to entry barriers: were there open markets in enrichment, new cheaper capacity would have forced the retirement of diffusion technology much sooner). Entry of new participants into the enrichment market is constrained by non-proliferation considerations, as well as by commercial interests. The enrichment industry is now being more closely watched with the discovery of the Pakistani enrichment smuggling network, which stole centrifuge technology from Urenco; see Braun and Chyba (2004).

Without market intervention, prices could fall to competitive levels; this implies there could be no economic profits in this industry for anyone but the Russians and Europeans. For this reason, the financial outlook of these uranium enrichers has been bleak, prompting a Standard and Poor's analyst to write:

> "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. . ." (These ratings were re-affirmed on April 24, 2008)

"A-" implies that Standard & Poor's believes that (1) "A" implies "economic situation can affect finance" and (2) the negative sign ("-") implies that it is likely to be downgraded; A- > BB > BB- > B+ > B- are lower and lower credit ratings for "non-investment" grade bonds, so called, "junk bonds." So, since 2002 USEC has been forced to pay junk bond rates on its debt, while trying to finance a new, First-of-a-Kind technology. This situation has been deteriorating; see Table II.

Table II. USEC Credit Ratings Report Card, 2002-2008

Standard & Poor's	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Corporate credit rating	BB	BB	BB-	B+	B-	B-	B-
Senior unsecured debt	NA	BB-	B	B	CCC	CCC	CCC
Outlook	Negative	Stable	Negative	Negative	Negative	Negative	Negative
Moody's	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Corporate credit rating	Ba1	Ba1	Ba2	B1	B1	B3	B3
Senior unsecured debt	NA	Ba2	Ba3	B2	B3	Caa2	unrated
Outlook	Negative	Negative	Review	Stable	Review	Negative	Negative

Sources: *USEC Annual Reports* (2002-2007) and *Form 10-K, December 31, 2008* (Feb. 26, 2009)

Therefore, assuring adequate diversity of enrichment capacity over the long term could be problematic without some more comprehensive market intervention (than continued subsidization from governments to private firms). Of course, a Russian-European duopoly in enrichment might provide an adequate diversity of supply. The U.S. Government must determine how many suppliers should be in the enrichment market to maintain some market competition or whether any form of market regulation is necessary or possible.

The U.S. Government has been subsidizing the USEC for over a decade (due to the Russian blend-down agreement), it is unlikely that USEC will survive without a continuous infusion of federal capital until ACP is finished. If it does survive, then it might not be competitive enough to grow larger than the Urenco and Areva plants in the United States, if only because these firms have more experience with centrifuge technology. If USEC cannot survive, then the U.S. Government will be forced to nationalize the remains of the American Centrifuge Plant to provide services to defense programs (e.g., naval reactors), as well as pay for the decommissioning of the gaseous diffusion facilities and any other outstanding USEC liabilities.

On the other hand, American electric utility demand can be supplied by Americans working at the Areva and Urenco plants in Idaho and New Mexico, and by the Russians through the extension of current contracts. Therefore, it is not in the American electric utilities' interest to support USEC's the high prices, but it might be in their interest to support the existence of USEC as a hedge against dependence on one or two suppliers. There might be no public support for USEC aside from those interest groups that have directly or indirectly benefited or will directly or indirectly benefit from the federal subsidies that have been given or will be given to USEC.

Unregulated enrichment markets will not necessarily lead to a socially optimal diversity of enrichment suppliers: a long-run equilibrium where the industry is *necessarily concentrated* such that there is no proliferating entry, but is *sufficiently diverse* so that no one national group can dictate prices, contract terms, or non-proliferation policy. United States decision makers should determine (1) whether a Russian-European duopoly is in the national interest of the United States given the dependence of the nuclear navy on domestically produced highly enriched uranium (uranium enriched above 20%), and (2) whether to forever subsidize USEC, or nationalize it before or after it is pushed by market forces and financial pressure to file for bankruptcy.

Appendix: A Microeconomic Engineering Model of Uranium 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"

This Appendix creates a top-down, microeconomic-engineering model to project levelized costs at facilities like Capenhurst. To account for the capital, labor, electricity, and other expenses, let the total annual cost of producing total annual SWU be

$$TC = p_K K + p_L L + p_E E + p_M M, \qquad \text{where} \tag{1}$$

- K is the total capital investment cost (TCIC, defined in EMWG 2007) measured in millions, M, of 2008 dollars, and p_K is the annual capital charge rate;
- L is the number of employees, 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; and
- M represents the cost of materials consumed, and p_M is the price of materials.[10]

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

$$AC = \Sigma\,(p_{KM} K + p_L L_t + p_E E_t)\,(1 + r)^{-t} \,/\, \{\, \Sigma\, SWU_t\,(1 + r)^{-t} \,\}, \tag{2}$$

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. (Following Harding, 2005, p. 9, there is an implicit assumption of a constant annual capacity factor of 100 percent, because "If machines are stopped, risk is they will not start again.")

Returns to scale in cost is the ratio of the percentage change in total cost, TC, with respect to a percentage change in output, SWU:

$$\mathrm{RS} = (\Delta TC/TC) \,/\, (\Delta SWU/SWU) \approx (d\,TC \,/\, d\,SWU) \,/\, (TC \,/\, SWU) \approx d \ln TC \,/\, d \ln SWU \quad (3)$$

For example, if output is increased by 10%, and total cost increases by less than 10%, then there are increasing returns to scale, and average costs are falling. If output is increased by 10%, and total cost increases by more than 10%, there are decreasing returns to scale, and average costs are rising. For many production processes, average costs fall with increases in capacity (because average fixed costs are falling). At some capacity range, average costs are constant, but beyond that range, average costs rise with decreasing returns to scale. This yields a "U"-shaped average cost curve.

However, in industries with increasing returns to scale (where there are large fixed, capital costs), the average cost curve continually declines throughout the relevant range of industry demand. This yields a "bath-tub-shaped" average cost curve, where average cost eventually increases at some very large size. This type of cost structure implies that large firms could have lower costs than smaller firms. If there is no arrangement to divide the market and profits, the smaller firms will be driven from the industry (or will never enter). At the limit, one large firm could dominate the industry.

The remainder of this Appendix proposes and tests whether there are increasing returns to scale in (1) capital, K (i.e., $\partial \ln K / \partial \ln Q$) and (2) labor, L (i.e., $\partial \ln L / \partial \ln Q$) for centrifuge capacity (there is not enough information to estimate returns to scale in energy and materials). With these input prices and estimates of the derivatives of the inputs with respect to changes in facility size, returns to scale in total cost are examined through constructing and analyzing the resulting average cost curves in Section A.4.

A.1. Estimating New Centrifuge Enrichment Facility Costs [11]

A.1.1. Estimating New Centrifuge Facility Capital Costs

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. Overnight construction cost, k_i, for new centrifuge facilities is estimated with information on five 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 centrifuge producing 320 SWU per year. USEC estimated the first stage will cost $3,500M in 2008 dollars for a capacity of 3.8M SWU. The facility could be completed by 2012 (USEC, 2007).

(2) The Urenco New Enrichment Facility (NEF) facility in New Mexico with a 3M 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 $1,500M (in 2006 dollars, or $1,650 in 2008 dollars); see WNA (2008).

(3) Areva is building a $2,000M, 3M-SWU-per-year facility in Idaho Falls, Idaho. Areva expects the ETC centrifuge-supplied facility (TC-12 machines with a capacity of 50 SWU per centrifuge per year) to start operating in 2014, and enter full production in 2019.

(4) The new George Besse II enrichment facility, with a capacity of 7.5M 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 € 3,000M (2003) (or $3,275M 2003 dollars, or $4,066M 2008 dollars); Autebert (2006) and WNA (2008).

(5) Brazil 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 that is initially producing about 10 SWU per centrifuge per year. [12] The estimated construction cost is about 541M 2006 Brazilian Real, or about $278M 2008 dollars (Cabrera-Palmer and Rothwell, 2008).

The descriptive statistics for these plant data are Table I. The variables have been scaled so their means are similar. Here, the minimum value for overnight cost, *k*, is 0.278 billion 2008 dollars and the maximum value is $4.066 billion. The minimum value for *SWU* is 0.203 million SWU per year, and the maximum is 7.5 million SWU per year. *RATE* (the rating of the centrifuge in SWU per year) is given in 100s of SWU per centrifuge, so the minimum value is 0.1 (x 100) SWU per centrifuge for Brazil and the maximum is 3.0 (x 100) SWU per centrifuge for ACP. Overnight cost is highly correlated with capacity size, *SWU*, (92%) and correlated (54%) with output rating, *RATE*; capacity size and output rating are somewhat correlated (17%).

With this information, linear and log-linear models of *k* are estimated and presented as functions of annual SWU capacity, SWU_i and $RATE_i$. The Ordinary Least Squares (OLS) parameter estimates are (where values in parentheses are standard errors; and * = 90% level of significance, ** = 95% level of significance, and *** = 99% level of significance):

$$k_i = \underset{(0.56)}{0.44} + \underset{(0.13)^{**}}{0.53}\ SWU_i \qquad (R^2 = 84.3\%,\ \text{F sig.} = 97.2\%) \tag{4.1}$$

$$k_i = \underset{(0.88)}{1.66} + \underset{(0.63)}{0.69}\ RATE_i \qquad (R^2 = 28.7\%,\ \text{F sig.} = 64.8\%) \tag{4.2}$$

$$k_i = \underset{(0.15)}{0.11} + \underset{(0.03)^{***}}{0.49}\ SWU_i + \underset{(0.76)^{**}}{5.05}\ RATE_i \qquad (R^2 = 99.3\%,\ \text{F sig.} = 99.3\%) \tag{4.3}$$

$$\ln(k_i) = \underset{(0.13)}{-0.09} + \underset{(0.09)^{***}}{0.76}\ \ln(SWU_i) \qquad (R^2 = 96.3\%,\ \text{F sig.} = 99.7\%) \tag{4.4}$$

$$\ln(k_i) = \underset{(0.37)^{*}}{0.99} + \underset{(0.30)^{*}}{0.73}\ \ln(RATE_i) \qquad (R^2 = 66.7\%,\ \text{F sig.} = 90.9\%) \tag{4.5}$$

$$\ln(k_i) = \underset{(0.15)}{0.15} + \underset{(0.09)^{**}}{0.63}\ \ln(SWU_i) + \underset{(0.10)}{0.20}\ \ln(RATE_i)\ , \qquad (R^2 = 98.7\%,\ \text{F sig.} = 98.7\%) \tag{4.6}$$

While $RATE_i$ explains some of the variance in k_i, most of the variance is explained by SWU_i (96% in the log-linear model). Further, the parameter associated with capacity is robust to the inclusion of $RATE_i$, i.e., the estimated coefficient on SWU_i in Equation 4.1 is not statistically different from the estimated coefficient on SWU_i in Equation 4.3, nor is the estimated coefficient on $\ln(SWU_i)$ in Equation 4.4 statistically different from the estimated coefficient on $\ln(SWU_i)$ in Equation 4.6.[13] From these results one can conclude *there are increasing returns to scale in capital*: with a scale factor of 0.76 and a standard error of 0.09, there is 95 percent confidence that the scale factor is not equal to 1.0, as it would be under constant returns to scale.

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. The IDC rate is a function of the expenditure rate, 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, assuming a lead time of 3 years. At a cost of capital of 5 percent, IDC adds 7.48 percent to the cost of the project. Following EMWG (2007), the contingency rate is 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), the model uses a 5 percent *real* cost of capital with capital cost amortization over 30 years, i.e., $p_K = 6.5$ percent. (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, the model assumes 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, $\mathrm{p_{KM}} = 6.5\% + 0.85\% = 7.4\%$.

A.1.2. Estimating New Centrifuge Facility Labor Costs

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, Areva announced that it would be hiring at least 250 full-time employees at Idaho, 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 3.4M SWU per year); this provides a benchmark and another observation. Because one of the observations is different from one in Table A.I, Table A.II provides the descriptive statistics and correlations for this data set.

The variables have been scaled so their means are similar. Here, the minimum value for the number of employees, *L*, is 1.0 (x 100) employees, and the maximum is 5 (x 100) employees. The minimum value for *SWU* is the same as above, but the maximum is 3.8 million SWU per year. *RATE* is as above, because it is assumed that Capenhurst and George Besse II use the same technology.

The number of employees is highly correlated (82%) with the both the number of SWU and with the *RATE*; *SWU* and *RATE* are positively correlated (57%). Together these correlations imply (1) centrifuges with higher annual output require more maintenance, as suggested by one astute referee,[x] and (2) much of the variance explained by *RATE* is also explained by *SWU*, so that they will not both be significant when they both appear in the same equation. With this information, linear and log-linear models of *L* (staff size) are estimated and presented as functions of annual SWU capacity and the rating of the centrifuge in SWU per year:

$$L_i = \underset{(1.06)}{0.46} + \underset{(0.36)^*}{0.91}\ SWU_i \qquad (R^2 = 68.6\%, \text{F sig.} = 91.7\%) \qquad (5.1)$$

$$L_i = \underset{(0.62)}{1.89} + \underset{(0.45)^*}{1.09}\ RATE_i \qquad (R^2 = 66.5\%, \text{F sig.} = 90.8\%) \qquad (5.2)$$

$$L_i = \underset{(0.86)}{0.68} + \underset{(0.35)}{0.59}\ SWU_i + \underset{(0.42)}{0.68}\ RATE_i \qquad (R^2 = 86.3\%, \text{F sig.} = 86.3\%) \qquad (5.3)$$

$$\ln(L_i) = \underset{(0.18)^{**}}{0.65} + \underset{(0.14)^{**}}{0.43}\ln(SWU_i) \qquad (R^2 = 76.0\%, \text{ F sig.} = 94.6\%) \qquad (5.4)$$

$$\ln(L_i) = \underset{(0.16)^{***}}{1.23} + \underset{(0.13)^{**}}{0.49}\ln(RATE_i) \qquad (R^2 = 82.2\%, \text{ F sig.} = 99.6\%) \qquad (5.5)$$

$$\ln(L_i) = \underset{(0.29)^{*}}{0.99} + \underset{(0.21)}{0.20}\ln(SWU_i) + \underset{(0.21)}{0.30}\ln(RATE_i) \qquad (R^2 = 87.9\%, \text{ F sig.} = 87.9\%) \qquad (5.6)$$

Here, unlike in the previous estimates, $RATE_i$ explains as much of the variance in L_i, as is explained by SWU_i. The parameter associated with capacity is robust to the inclusion of $RATE_i$, i.e., the estimated coefficient on SWU_i in Equation 5.1 is not statistically different from the estimated coefficient on SWU_i in Equation 5.3, nor is the estimated coefficient on $\ln(SWU_i)$ in Equation 5.4 statistically different from the estimated coefficient on $\ln(SWU_i)$ in Equation 5.6. The linear forms are not as well estimated as the log-linear forms. Also, when both explanatory variables are present, none of the coefficients are significant. While Equation 5.5 has a higher R^2 than Equation 5.4 (which is important when making forecasts, as is done in the next section), the centrifuge rating is not known for the centrifuges in all centrifuge enrichment plants (e.g., those in Russia). Therefore, I will use Equation 5.4 for hypothesis testing and forecasting. With the scale factor equal to 0.43, and a standard error of 0.14, there is 98 percent confidence in rejecting constant returns, adjusting for degrees of freedom. Therefore, one can also conclude *there are increasing returns to scale in labor*.

Next, following Cabrera-Palmer and Rothwell (2008), the model uses a “fully burdened” average annual salary of \$60,000 in Brazil, based on a base salary of approximately \$35,000 per year and a 70 percent burden rate (from EMWG 2007). The model uses a burdened average annual salary in France and the United States of \$120,000, based on information in Enrichment Technology Company (2007). The model assumes the labor rates have not increased since 2006.

A.1.3. Estimating New Centrifuge Facility Energy Costs

Third, the electricity consumption for ETC and ACP centrifuges are from WNA (2008): 50 kWh/SWU to run the centrifuges, and 62.3 kWh/SWU to run the plant. 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), and updating the price to 2008 dollars, let the delivered price of electricity be $106.72/MWh (or $0.107/kWh), which includes transmission and distribution fees. Because generation is one-half of total costs, the generation cost is approximately $53.36/MWh or $0.053/kWh.

A.1.4. Estimates of New Centrifuge Facility Costs

Table A.III 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. Table A.III shows

- 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 high as the cost at the ACP, and almost three times as much as cost at the Urenco facilities.

A.2. Projecting Replacement Costs of Operating Centrifuge Facilities

This section approximates the cost structure of the existing commercial centrifuge facilities owned by Urenco, JNFL, and Rosatom. See Tables A.IV and A.V. Urenco has three production facilities at Capenhurst, United Kingdom, with 3.4M SWU; Almelo, Netherlands, with 2.9M SWU; and Gronau, Germany, with 1.8M SWU. The overnight replacement costs (in 2008 dollars) are estimated using Equation (4.4). Because these facilities have already been built and some of the capital has been depreciated, there is no contingency or IDC, i.e., 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 about 10 percent.) Here, Urenco and JNFL use a real cost of capital of 5 percent. 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 its small size (also Japanese levelized costs could be higher due to lower capacity factors at Rokkasho: as its capacity factor declines, its average costs could become the world's highest.)

The same analysis is applied to estimate the costs at Rosatom's centrifuge facilities in Novouralsk (UEKhK, Sverdlovsk Oblast) with 12.45M SWU, Zelenogorsk (EKhZ, Krasnoyarsk Kray) with 7.39M SWU, Seversk (SKhK, Tomsk Oblast) with 3.65M SWU, and Angarsk (Irkutsk Oblast) with 2.5M SWU. (See International Panel on Fissile Materials 2007.) Again, the replacement values of the facilities can be modeled with Equation (4.4) and labor requirements with Equation (5.4). In determining appropriate parameter values, consider 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, assume that (1) the real cost of capital is 2.5%, leading to a capital recovery factor of 4.8% (versus 6.5% for the other centrifuge facilities), (2) the burdened cost of labor is $60,000 equal to that in Brazil, and (3) the cost of electricity of $53/MWh (implicitly assuming that the cost of transmission and distribution is zero). See Table A.V. The estimated levelized cost in 2008 dollars is between $28 for the largest facility and $45 for the smallest facility, lower than at all other international facilities. It is possible that costs are even lower, as suggested in Bukharin (2004).

A.3. Projecting Costs of the Diffusion Facilities

Finally, the model is used to approximate the cost structure of the existing commercial diffusion plants owned by USEC and Eurodif. See Table A.VI. 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, approximated with the model of centrifuge technology, are of second order importance). Using the same technique for projecting investment costs as above, the current investment costs (*replacement value*) for each diffusion plant is about \$4,000 M. The model assumes a 2.5% cost of capital to determine the annual capital charge. 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, assume dedicated electricity generators at \$53/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 enrichment industry (with almost half the world's capacity). These plants are scheduled to retire by 2015.

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

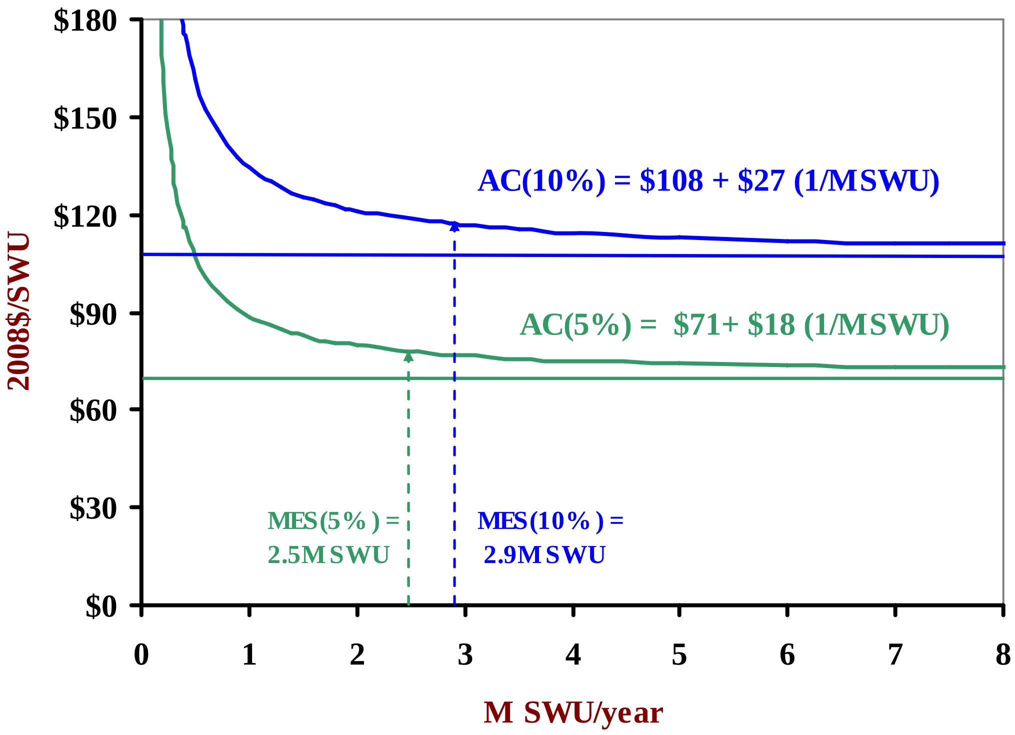
A reciprocal functional form is used to estimate the relationship between average cost (AC) and size (SWU) in these simulated data:

$$AC = \gamma + \delta (1 / SWU). \tag{5}$$

Average cost is calculated for hypothetical plants of many sizes at costs of capital of 5% and 10%. The relationship between average costs and the reciprocal of size is estimated using OLS. Figure A.1 represents these relationships, where the OLS results are shown on the figure. (Here, increasing returns to scale are nearly exhausted at the "Minimum Efficient Scale" (MES) between 2.5 and 2.9 million SWU, which is where costs are not more that 10 percent of the asymptote, equal to the constant, γ.) As an example, for a plant with a capacity of 1 million SWU per year with *r* = 10%, the levelized average cost would be approximately \$107.63 + \$26.88 = \$135/SWU in 2008 dollars. (Here, “levelized average cost” is calculated assuming all costs and all outputs are equal across time; when this is true, “levelized cost” in cost engineering is equal to “average cost” in microeconomics.)

Here, it is unknown where the average cost curve, as portrayed in Figure A.1., might begin to increase. Given that Russia could have increased capacity in any of their facilities, and yet capacity at Novouralsk (UEKhK) has been increased to at least 12.45 M SWU per year, it is reasonable to conclude that costs are not yet increasing at UEKhK. So it is unlikely that average costs at a generic centrifuge facility begin to increase before 12 M SWU per year, which is four times the size of any first-stage plants being built in the United States, and is off the graph in Figure A.1.

Figure A.1. Estimated Cost Curves, Centrifuge Technology



TABLES

Table A.I. Descriptive Statistics of Capital Variables

	Descriptive Statistics				*Correlation*		
Variables	**Mean**	**Std Dev**	**Min**	**Max**	*K*	*SWU*	*RATE*
K ($B)	2.299	1.513	0.278	4.066	1	91.8%	53.6%
SWU (M)	3.501	2.620	0.203	7.500	91.8%	1	16.8%
RATE (100s)	0.920	1.176	0.100	3.000	53.6%	16.8%	1

Table A.II. Descriptive Statistics of Labor Variables

	Descriptive Statistics				*Correlation*		
Variables	**Mean**	**Std Dev**	**Min**	**Max**	*L*	*SWU*	*RATE*
L (100s)	2.900	1.567	1.000	5.000	1	82.8%	81.6%
SWU (M)	2.681	1.424	0.203	3.800	82.8%	1	56.6%
RATE (100s)	0.920	1.176	0.100	3.000	81.6%	56.6%	1

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

Firm **Plant**	(2008$)	**USEC** **ACP**	**Urenco** **NEF**	**Areva** **Idaho**	**Eurodif** **Besse II**	**Brazil** **Resende**
Plant Capacity	t SWU/yr	**3,800**	**3,000**	**3,000**	**7,500**	**203**
Overnight Cost	$M	$3,500	$1,650	$2,000	$4,066	$278
Total Capital Invest Cost	$M	$4,152	$1,957	$2,372	$4,823	$330
Capital/SWU	**$/SWU**	**$71.07**	**$42.44**	**$51.44**	**$41.83**	**$105.68**
Staff Size	people	500	210	250	481	100
Annual Fully Burden Salary	$k/yr	$120	$120	$120	$120	$60
Labor/SWU	**$/SWU**	**$15.79**	**$8.40**	**$10.00**	**$7.70**	**$29.56**
Electricity Consumption	kWh/SWU	62	62	62	62	100
Electricity Price	$/MWh	$107	$107	$107	$107	$107
Electricity/SWU	**$/SWU**	**$6.65**	**$6.65**	**$6.65**	**$6.65**	**$10.67**
Materials/SWU	**$/SWU**	**$9.21**	**$5.50**	**$6.67**	**$5.42**	**$13.69**
Annual Total Costs	$M	**$390**	**$189**	**$224**	**$462**	**$32**
Levelized SWU Cost	$/SWU	**$103**	**$63**	**$75**	**$62**	**$160**

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

Firm **Plant**	(2008$)	**Urenco** **Capenhurst**	**Urenco** **Almelo**	**Urenco** **Gronau**	**JNFL** **Rokkasho**
Plant Capacity	t SWU/yr	**3,400**	**2,900**	**1,800**	**1,500**
Overnight Cost	$M	$2,342	$2,076	$1,445	$1,095
Total Capital Invest Cost	$M	$2,342	$2,076	$1,445	$1,095
Capital/SWU	**$/SWU**	**$44.82**	**$46.56**	**$52.21**	**$56.98**
Staff Size	people	340	317	257	219
Annual Fully Burden Salary	$k/yr	$120	$120	$120	$120
Labor/SWU	**$/SWU**	**$11.99**	**$13.10**	**$17.12**	**$20.99**
Electricity Consumption	kWh/SWU	62	62	62	62
Electricity Price	$/MWh	$107	$107	$107	$107
Electricity/SWU	**$/SWU**	**$6.65**	**$6.65**	**$6.65**	**$6.65**
Materials/SWU	**$/SWU**	**$6.89**	**$7.16**	**$8.03**	**$8.76**
Annual Total Costs	$M	**$239**	**$213**	**$151**	**$117**
Levelized SWU Cost	$/SWU	**$70**	**$73**	**$84**	**$93**

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

Firm **Plant**	(2008$)	**Tenex** **UEKhK**	**Tenex** **EKhZ**	**Tenex** **SKhK**	**Tenex** **Angarsk**
Plant Capacity	t SWU/yr	**12,450**	**7,390**	**3,650**	**2,500**
Overnight Cost	$M	$6,282	$4,226	$2,472	$1,854
Total Capital Invest Cost	$M	$6,282	$4,226	$2,472	$1,854
Capital/SWU	**$/SWU**	**$24.11**	**$27.32**	**$32.36**	**$35.44**
Staff Size	people	601	478	350	297
Annual Fully Burden Salary	$k/yr	$60	$60	$60	$60
Labor/SWU	**$/SWU**	**$2.90**	**$3.88**	**$5.76**	**$7.12**
Electricity Consumption	kWh/SWU	62	62	62	62
Electricity Price	$/MWh	$53	$53	$53	$53
Electricity/SWU	**$/SWU**	**$3.32**	**$3.32**	**$3.32**	**$3.32**
Materials/SWU	**$/SWU**	**$5.05**	**$5.72**	**$6.77**	**$7.42**
Annual Total Costs	$M	**$440**	**$297**	**$176**	**$133**
Levelized SWU Cost	$/SWU	**$35**	**$40**	**$48**	**$53**

Table A.VI. 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 **Plant**	(2008$)	**USEC** **Paducah**	**Areva** **Eurodif**
Plant Capacity	t SWU/yr	8,000	11,300
Overnight Cost	$M	$4,488	$5,836
Total Capital Invest Cost	$M	$4,488	$5,836
Capital/SWU	**$/SWU**	**$18.98**	**$25.82**
Staff Size	people	495	576
Annual Fully Burden Salary	$k/yr	$120	$120
Labor/SWU	**$/SWU**	**$6.88**	**$8.61**
Electricity Consumption	kWh/SWU	2,500	2,200
Electricity Price	$/MWh	$53	$53
Electricity/SWU	**$/SWU**	**$133.38**	**$117.37**
Materials/SWU	**$/SWU**	**$3.97**	**$5.40**
Annual Total Costs	$M	**$1,826**	**$1,674**
Levelized SWU Cost	$/SWU	**$163**	**$157**

ENDNOTES

[1] HHI is the sum of the squares of the percentage shares across the industry. For example, an industry with 10 firms, all with an equal share, would have an HHI equal to 10 x $(10)^2$ = 1,000. According to the U.S. Department of Justice and Federal Trade Commission (1997) Section 1.51 states, "Markets in which the HHI is between 1000 and 1800 points are considered to be moderately concentrated, and those in which the HHI is in excess of 1800 points are considered to be concentrated. Transactions that increase the HHI by more than 100 points in concentrated markets presumptively raise antitrust concerns under the Horizontal Merger Guidelines issued by the U.S. Department of Justice and the Federal Trade Commission."

[2] On the early history of privately-held centrifuge enrichment capacity, see Rothwell (1974).

[3] Although this paper focuses on estimating returns to scale at the level of average SWU costs, many of these increasing returns could arise in the manufacture of centrifuges, i.e., the equipment component of overnight costs, *k*. However, without a detailed description of structure and equipment costs for a cross-section of facilities, it is not possible to separate the various sources of increasing returns to scale in capital.

[4] In 129 S.Ct. 878 (January 29, 2009) the U.S. Supreme Court reversed a lower federal court decision that enrichment was not a "good," as defined in U.S. anti-dumping law. The lower court must now determine whether Eurodif "dumped" uranium enrichment, and if so, whether USEC was injured and to what extent. Still, this paper occasionally refers to enrichment as a "service."

[5] Because of the trade-off between uranium and uranium enrichment, the nuclear power plant operator can purchase either less uranium and more SWU, lowering the percentage of U^{235} in the tails, or more uranium and less SWU, with an increase in the percentage of U^{235} in the tails. See Bunn, et al. (2003, p.94) on the calculation of the optimal tails assay. Note, however, that the approximation in their equation (A.16) fixes the feed assay at 0.711%. Therefore, it cannot be used to determine the optimal re-enrichment of tails or reprocessed uranium.

[6] These estimates are used to illustrate the international SWU market and are based on statistical results, thus there could be an error of ±10 to 20 percent based on the standard errors of the estimation. Construction costs are deflated following the U.S. GDP implicit price deflator. Electricity prices are deflated following the U.S. Producer Price Index for Electricity Generation, Distribution, and Transmission, see http://data.bls.gov.)

[7] 2020 was chosen because the Russia-United States blend down agreement will be terminated, the gaseous diffusion capacity will be retired, and the enrichment capacity under current planning and construction should be completed, including the Areva plant in Idaho.

[8] This assumes that Russia continues to use a lower than optimal tails assay to fulfil fuel contracts by using less Russian uranium, thus increasing "domestic" SWU consumption and reducing SWU on the world market. So, in Figure 3, only one-half of Novouralsk's capacity is competing in the world market. See Rothwell (2008).

[9] It is difficult to know contract prices, which could be much lower than spot market prices, and thus industry profits could be much lower than the maximum revenue of $4,500M. However, the industry could still be following the contractual practice of the U.S. Atomic Energy Commission (U.S. AEC, 1972, p. 46): "Applicable charges for enriching services and related services will be those in effect at the time of delivery of enriched uranium to the customer." See discussion in Rothwell (1980, p. 255).

[10] Although EMWG (2007) recommends financing plant decommissioning through a sinking fund, because decommissioning accounting for multiple-owner facilities is so complex, the decommissioning contribution is ignored in this analysis.

[11] While parameter values are estimated using econometric models, the analysis could also be presented in parametric form; however, it is easier to understand the qualitative conclusions when presented with numeric estimates, even though these might not be the "true" values given the proprietary nature of the cost and technological data.

[12] Before analyzing this information, note that the model is based on three centrifuge technologies at different maturities: The Urenco TC-12 centrifuge has been in commercial operation for more than a decade and can be reproduced at Nth-of-a-Kind cost. The smaller Brazilian centrifuge is in its First-of-a-Kind commercial deployment. The ACP larger centrifuge is being scaled up from prototype to commercial size. Consider the estimated SWU per centrifuge in Guizzo (2006, p. 6): “The less technically advanced machines, such as those reportedly used by Iran, each have a capacity of 3 SWU per year. State-of-the-art machines, such as those used by Urenco, are estimated to have a capacity of 50 to 100 SWU. The new American centrifuges are designed to operate at 300 SWU, assuming they will work. Brazil's centrifuges have a capacity of around 10 SWU or a little more, sources familiar with the project told me. These sources, who spoke on condition of anonymity because of the classified nature of the project, say that the machines are nearly 2 meters tall and are supercritical. They add that Brazilian navy researchers are now attempting to increase the length of the rotor without having to redesign its driving and bearing systems. That modification, they say, could improve the machines' performance.” Therefore, these are conditional estimates that should be revised when more information is publicly available.

[13] Several functional forms were estimated, including semi-log, reciprocal, and log-reciprocal. See Johnston and Dinardo (1997, p. 44). Also, the number of centrifuges (equal to plant SWU per year divided by SWU per machine per year) was also used as an explanatory variable, but was not significant in any of the OLS estimates. The linear, log-linear, and log-reciprocal models had the highest explanatory power, and no model yielded decreasing returns to scale. This was also true for Equations 5, discussed below.

[14] See Upson (2001, p. 1): “The superiority of the no-maintenance philosophy over larger diameter, longer centrifuges requiring maintenance, was never in doubt.”

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